Institute of Hydrology

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TANZANIA URBAN SECTOR

ENGINEERING PROJECT

YIELD ESTIMATES FOR TANGA

AND MOROGORO

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Executive summary

This report is presented to Gibb (Eastern Africa) Ltd as part of the hydrological study phase of the Tanzania Urban Sector Engineering Project being coordinated by Howard Humphreys (Tanzania) Ltd. The work carried out centred on the water supply of two towns: Morogoro, inland about 200 km west of Dar-Es-Salaam, and Tanga, on the coast to the north near the Kenyan border. For each town, assessment of the reliable yield of an existing reservoir was required. Additionally for Morogoro, assessment of the potential yield of nearby rivers and spring sources was also needed.

This report summarises the various data collected to carry out these tasks, and describes their subsequent validation and processing. For the river yield analyses, daily flow data were required, and these were derived from the supplied stage data and fitted rating curves; in all cases the record lengths supplied were long enough for meaningful analysis. The reservoir yield analyses were carried out on a monthly time scale, and long inflow data series, of the order of at least 60 years, were needed. These were not available, either directly or indirectly from analysis of the reservoir water level and outflow records. Part of the work therefore involved extending flow series using historical rainfall data and the Pitman rainfall-runoff model. Additional data requirements comprised rainfall records, evaporation estimates and details of the reservoir characteristics and operation.

The results of this study give the yield of Mabayani Dam near Tanga that can be guaranteed to 98 % reliability as 102000 m^3day^{-1}, and the yield of Mindu Dam at Morogoro that can be guaranteed to 98 % reliability as 52000 m^3day^{-1}. Both the dams are threatened by siltation. It is estimated that 20 years after dam construction, the 98 % reliable yields will be reduced to 97000 m^3day^{-1} and 47000 m^3day^{-1} at the Mabayani and Mindu Dams respectively. However, it is recommended that studies of sediment transport and siltation rates are carried out in order to improve estimates of the rate of decline of the dam capacity. Raising the Mindu Dam by the maximum proposed 2.5 m is estimated to increase the 98 % reliable yield by around 50 %.

The low flow analyses for the river yield studies show that the present rate of abstraction at the existing Mambogo intake on the Morogoro river is likely to fail every 4 to 6 years for periods of up to 10 days, and should not therefore be increased. The results for the rivers Wami and Mgeta show that either may provide a potential additional source, downstream water rights permitting. For the Wami at Dakawa the 98 % reliable yield is 69000 m^3day^{-1}. For the Mgeta at Mgeta the results are less certain because of a questionable period of published flow data between January 1971 and June 1976, but a 98 % reliable yield of 36000 m^3day^{-1} was determined using flow data computed using the rating equation derived in this study.

Insufficient data were available to estimate the yield of the spring sources at Morogoro, and a regular gauging program must be implemented before a study of the potential yields can be made.

Contents

1. Introduction

This report is presented to Gibb (Eastern Africa) Ltd as part of the hydrological study phase of the Tanzania Urban Sector Engineering Project being coordinated by Howard Humphreys (Tanzania) Ltd. The report describes analyses carried out to estimate the yield of Mabayani Dam near Tanga and Mindu Dam at Morogoro. Figure 1.1 shows the locations of Tanga and Morogoro. It has been proposed that the capacity of Mindu Dam could be increased by raising the dam, and so the yield analysis has been done for the current level and for various levels up to the maximum proposed (Gibb, 1986). Analyses to assess the yield of the Morogoro river and some spring sources, and the potential yield of the nearby Wami and Mgeta rivers, are also described.

Principal data requirements for the analyses conducted were good quality, long-term flow series at the gauging stations in the project areas. For the reservoir yield analyses, long enough records were not available, either directly or indirectly from analysis of the reservoir water balance. Therefore, a major component of the study entailed generating inflow data series from historical rainfall series. Consequently, an additional data requirement was long-term rainfall data. At the river gauging stations, stage records and current meter measurements were provided. Therefore, rating curves had to be fitted to the current meter measurements, before the stage data could be converted to flows. Estimates of open water evaporation were also collected. The time scale of the study prevented rigorous validation of the data, but basic checks were made and these are described. Also described are the processing and analysis of the data, and interpretation of the results. The background information and datasets used in this study were collected in the course of a 5-day visit to Tanzania which included a fieldtrip to the Morogoro site, and a 3-day visit to the Gibb office in Kenya. The review, checking and analyses of the data were carried out in the UK.

After a brief consideration of the methodologies, the report is split into two main sections: one for Tanga describing the yield analysis for Mabayani Dam, and one for Morogoro describing the yield analysis for Mindu Dam and the yield analyses of the rivers and springs. This necessarily entails some repetition of methodology, but was considered the best approach for clarity and future reference.

1.1 RESERVOIR YIELD ANALYSIS

A large number of reservoir yield analysis procedures are available, and are described in detail in McMahon & Mein (1986). The approach selected for this study was the failure rate method, described briefly below. The data requirements for reservoir yield analysis include:

- A long series of monthly inflows to the reservoir
- A long series of monthly rainfalls on the reservoir
- Average monthly open water evaporation rates
- The area-capacity characteristics of the reservoir

Where the inflow records are too short to allow estimation of the reliability with any certainty, as was the case in this study, it is necessary to extend the records using historic rainfall data.

The failure rate method is most suitable for final design and yield assessment of storages with critical periods of less than 12 months, and requires a single pass through the inflow series once the starting state has been determined. The assumptions of the method are that the reservoir is initially full, and that the historical data sequence is representative of future river flows. A monthly reservoir water balance is carried out and the number of annual failures of any duration is noted. The probability of failure is the number of annual failures expressed as a percentage of the total number of years of simulation.

1.2 RIVER YIELD ANALYSIS

In order to ascertain the reliable yield of a river it is necessary to establish the recurrence interval of low flow conditions. On unregulated rivers, low flows occur during periods of little or no rainfall when river water originates from natural storage within the catchment. Low flow frequency analysis gives frequency curves which show the proportion of years, or equivalently the average interval between years, in which the river flow falls below a given discharge. Such curves can be used to determine the probability of occurrence of a flow event of specified magnitude.

The data requirements for river yield analysis are primarily good quality daily mean flow data. For any period of D-days duration, the method of deriving a low flow frequency curve is essentially a 5-step procedure:

- Determine the minimum consecutive D-day flow in each year
- Rank them from highest to lowest
- Assign a plotting position to each rank using the Weibull plotting position
- Plot the discharge against the plotting position
- Draw a smooth curve through the points

Low flow frequency analysis is described in more detail in McMahon & Mein (1986) and in Gustard *et al.* (1992).

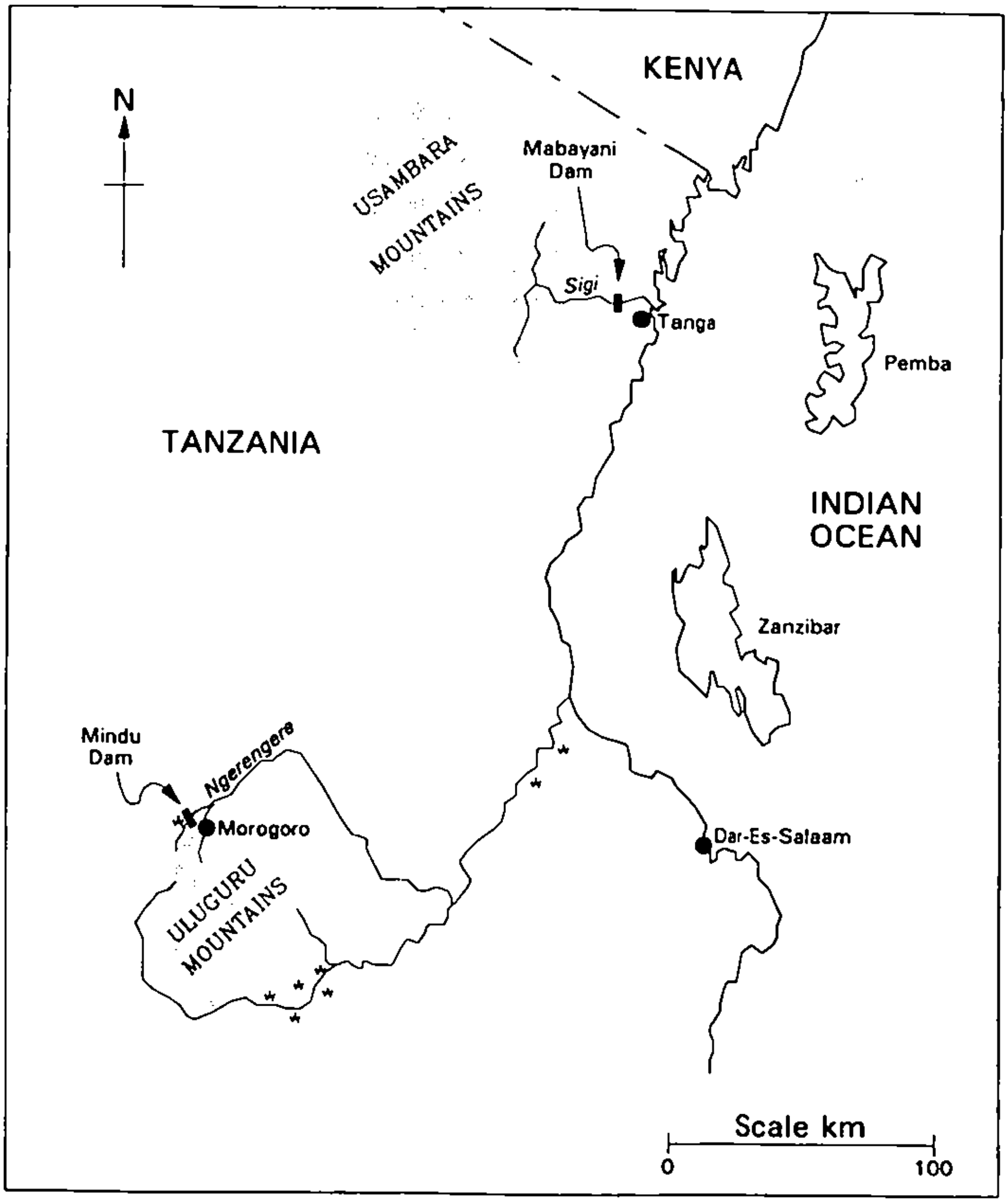

Figure 1.1 Location map showing Tanga and Morogoro

2. Tanga

2.1 BACKGROUND

Tanga, the second port of Tanzania, is situated on the coast to the north of Dar-Es-Salaam, about 65 km south of the Kenyan border, as shown in Figure 1.1. Formerly an important region for sisal production, the area is now dominated by dairy farming and ranching, industrial manufacturing and harbour and port operations. The town is on the coastal plain, so the low-lying topography is flat or gently undulating, though the ground gradually rises to the Usambara Mountains in the west. The geology comprises relatively recently deposited sandstones, with siltstones and clays on the coastal plain, giving loamy and sandy soils of variable drainage. The region has a humid equatorial climate with an annual average rainfall of around 1300 mm, falling primarily between April and June, but also between October and December.

The Tanga water supply system has been developed over most of this century. The earliest water supply was based on groundwater abstraction via boreholes, but expansion of this network in the late 1960s was deemed impracticable due to the geological conditions and the proximity of the sea. JBG (1972) proposed that the future water supply should be from the Sigi river which discharges into the sea about 5 km north-west of Tanga, and in 1978 Mabayani Dam, on the Sigi river about 20 km west of Tanga, was completed (JBG, 1979).

The hydrology of the Sigi river was studied and reported on in the preliminary design reports preceding the construction of Mabayani Dam (JBG, 1972; JBG, 1974), and again for the Tanga Master Plan (Interconsult, 1984). The design yield of the reservoir at Mabayani Dam was estimated at 26000 m^3day^{-1}. The hydrology was updated in 1983 when it was suggested that the potential draw-off was actually nearer 60000 m^3day^{-1}, more than twice the design yield (JBG, 1983). The dam is threatened by pollution, mainly from sisal factories, and by sedimentation e.g. in January 1993 landslides in the upper part of the catchment caused a heavy sediment load in the river.

JBG (1980) reveal that at certain times of the year Mabayani reservoir stratifies near the dam, and there is little, if any, dissolved oxygen below this stratification, rendering the reservoir useless for water supply. The reason put forward as the cause of this stratification was the decay of organic matter, such as vegetation washed downstream and algae living in the reservoir.

JBG (1986) considers the potential effects of various land use change scenarios in the Mabayani Dam catchment, and reports that deforestation through unauthorised logging within the woods and forest reserves is becoming an increasing problem. Deforestation results in increased soil erosion and increased sediment loads in the river system. This causes the catchment to become flashier, increasing the flood peaks and reducing the low flows, and possibly precipitating turbidity crises such as that in 1992. The ultimate effect would be to decrease the live storage of the dam. Long-term data on siltation and sediment transport are fairly non-existent in the greater part of East Africa, and it is recommended that studies of sediment transport and siltation rates are carried out in order to improve estimates of the rate of decline of dam capacity.

Potential sources of water to satisfy future requirements include extending Mabayani Dam, reverting to borehole supply in some places, diverting water into the Sigi river from the nearby Pangani river, and providing additional storage in the upper part of the catchment.

2.2 YIELD ASSESSMENT FOR MABAYANI DAM

2.2.1 The Sigi catchment

The Sigi river rises in the Usambara Mountains to the west of Tanga (Figure 2.1). It has two primary tributaries, the Sigi which flows initially eastwards and then northwards, and the Muzi which flows initially southwards, until their confluence. The riverthen flows eastwards out of the Usambara mountains near Lanconi, through Mabayani Dam, and onwards to the sea just north of Tanga. There is a gauging station at Lanconi where the catchment area is 705 km^2. The catchment area at Mabayani Dam is 870 km^2. The upper catchment is mountainous and steep, the Usambara mountains being composed of ancient faulted metamorphic rocks which give rise to well-drained sandy, clayey and loamy soils. In contrast, the lower catchment, descending to the coastal plain, is hilly and undulating. Vegetation cover is good, comprising forest interspersed with tea plantations in the upper parts and giving way to sisal plantations, bush and grazing land in the lower parts. The annual average rainfall of the catchment varies from around 1000 mm at the dam, up to 2000 mm in the mountains.

The aim of the current study was to determine the original yield of Mabayani Dam, and to predict the potential yield following 20 years of reservoir sedimentation.

2.2.2 Flow data

The primary flow gauging station in the Sigi catchment is at Lanconi, about 12 km upstream of Mabayani Dam. Table 2.1 gives details of the gauge and available record.

Table 2.1 Details of flow gauging stations for Mabayani Dam

Gauge No.	Name	Area (km^2)	Period of record	No. of years
1C1	Sigi at Lanconi	705.0	1957-1990	34

Flow data for this site were provided by the Ministry of Water, Energy and Minerals (MAJI) in the form of daily, and sometime sub-daily, stage values together with current meter measurements and rating equations. The MAJI rating equations were:

For the period up until 09/07/64:

$$Q = 18.007(h - 0.07)^{1.5159}$$

For the period after 29/09/64:

$$Q = 17.917(h - 0.13)^{2.3405} \qquad hmax = 1.52 \text{ m}$$
$$Q = 38.769(h - 0.80)^{1.2144}$$

Figure 2.2 shows all the current meter measurements provided, and clearly identifies the switch in the rating for stage less than 1.0 m that occurred between July and September 1964 when new gauges were installed. For stage greater than 1.0 m, the current meter measurements do not indicate a change in rating. The MAJI ratings were examined and found to be generally acceptable, apart from a discontinuity in the second rating at the 1.52 m change-over point.

Before July 1976, only 5 current meter measurements were made at stage greater than 1.0 m. Since for stages greater than 1.0 m, the upper part of the rating does not appear to have changed over time, all the measurements with stage greater than 1.0 m were used to fix the upper part of the rating for this study. In addition, an assumption was made that the switch in the lower part of the rating occurred on 10/07/64. The rating equations thus developed by IH were:

For the period until 09/07/64:

$$Q = 14.630(h + 0.033)^{1.719}$$

For the period from 10/07/64:

$$Q = 16.540(h - 0.055)^{2.800} \qquad hmax = 1.07 \text{ m}$$
$$Q = 14.630(h + 0.033)^{1.719}$$

Figures 2.3a and 2.3b show these IH(1994) ratings compared to the rating equations supplied by MAJI. For the period from 10/07/64 the rating equations are very similar, but for the period before this, the IH(1994) rating results in slightly higher flows for stage measurements greater than 2.0 m. Following conversion of the stage data into flow using the IH(1994) rating, mean monthly flow values were abstracted. Figures 2.4a and 2.4b compare these mean monthly flow values with the limited record published in the MAJI Hydrological Yearbooks, and show the two series agree well, except for a short low flow period in 1964. Since it is the overall monthly volumes that are of interest in reservoir yield analysis, the flow record derived by IH was considered acceptable for the current study.

The flow record at Lanconi was used to generate the inflow series to Mabayani Dam. However, although this is quite a long record, it is too short to allow a good estimate of reliability of the reservoir yield to be made. Therefore, the flow record was extended using longer-term rainfall data. This is described in section 2.2.6.

2.2.3 Rainfall data

There are 6 potentially useful raingauges on or near the Mabayani Dam catchment, as shown in Figure 2.1. Table 2.2 gives details of the gauges and the records collected from each gauge. The rainfall data were collected as monthly computerised totals from the Directorate of Meteorology; there was insufficient time to allow any checking of the raw data. Only the raingauge at Amani in the upper catchment has a particularly long record; it has an unbroken 70 years of monthly data from 1921, and no trends are apparent on a cumulative mass plot. The other gauges, situated at lower altitudes and in the lower catchment, have shorter records and missing periods are common.

Table 2.2 *Details of raingauges for Mabayani Dam*

Gauge No.	Name	Altitude (m)	Period of record	No. of years
953803	Amani	911	1901-1990	89
953830	Lwengera	335	1951-1989	38
953841	Longuza	168	1960-1989	29
953853	Lanconi	122	1966-1989	23
953854	Mjesani	122	1966-1989	23
953863	Bombwera	189	1966-1989	23

In order to extend the flow series at Lanconi, and enable a long series of reservoir inflows to be generated, it was necessary to have monthly catchment rainfall figures for both the Lanconi catchment and the dam catchment. Long series of monthly rainfalls at the dam site itself were also required. The short record lengths at 5 of the 6 gauges prevented use of a method such as Theissen polygons to calculate the long series of catchment average rainfalls, since the short records would themselves have to be extended first. Table 2.3 shows the correlation coefficients between the monthly totals at the shorter-term raingauges and at Amani for periods of overlap.

Table 2.3 *Correlation coefficients for monthly rainfall between Amani and other stations*

Gauge	Correlation coefficient
Lwengera	0.84
Longuza	0.88
Lanconi	0.69
Mjesani	0.64
Bombwera	0.57

These correlation coefficients indicate that although the stations may not necessarily be receiving rainfall from the same storms, the long-term pattern of rainfall at each station is similar. The lower coefficients e.g. Bombwera, reflect those gauges which showed trends or changes in slope when plotted against Amani in a double mass plot. JBG (1983) provide an isohyetal map of the area, reproduced here as Figure 2.5. Some simple checks ensured that the average annual rainfall totals at each of the raingauges put the gauge in the right band on the map. The isohyetal method was used to determine the catchment average rainfall total for each area. The results are tabulated in Table 2.4. The ratio of the catchment average rainfall total to the average annual rainfall at Amani (1903 mm) was applied to the 70-year Amani record to derive the long-term catchment average rainfall series for each area.

Table 2.4 *Catchment average rainfall totals for sites around Mabayani Dam*

Site	Catchment rainfall (mm)
Lanconi catchment	1482
Mabayani catchment	1413
Mabayani Dam	1025

2.2.4 Climate data

A comprehensive study of potential evaporation in Tanzania (Woodhead, 1968) concluded that of the various evaporation estimates available, the Penman estimate of potential evaporation (Penman, 1948) should be regarded as the most suitable evaluation of open water evaporation for tropical East Africa. Unfortunately, few of the meteorological stations in Tanzania were equipped to measure all the variables necessary for the computation of open water evaporation. The report describes the derivation and application of the various techniques developed for assessment of these unobserved parameters, and presents results for 57 sites, including Tanga and Amani, using data from the early 1940s to 1964.

As these open water evaporation estimates are some 25 years old, attempts were made to try and collect some more recent meteorological data from which to derive better estimates. The nearest current site to Mabayani Dam is Kalimawe, some distance away to the north-west. However, the recent record for this station was very fragmentary. With time restrictions preventing another search for further data, the 1968 published values were used. Because evaporation is a very conservative variable which changes little from year to year, taking the mean of the individual monthly totals provides a reasonable method for estimating long-term annual evaporation, and use of an old record is justified.

Table 2.5 *Open water evaporation figures (mm)*

Site	Jan	Feb	Mar	Apr	May	Jun
Amani	172.0	165.0	156.0	108.0	99.0	104.0
Tanga	227.0	215.0	220.0	180.0	172.0	162.0
Lanconi	199.5	190.0	188.0	144.0	135.5	133.0
Dam	224.4	212.6	216.9	176.6	168.5	159.2

Site	Jul	Aug	Sep	Oct	Nov	Dec	Total
Amani	98.0	101.0	112.0	128.0	141.0	1158.0	1542.0
Tanga	162.0	179.0	183.0	197.0	197.0	219.0	2313.0
Lanconi	130.0	140.0	147.5	162.5	169.0	188.5	1927.5
Dam	158.9	175.3	179.6	193.7	194.3	216.1	2276.1

The evaporation figures required are mean monthly totals for the Lanconi catchment, for use in flow record extension, and for the reservoir at Mabayani Dam for use in the yield analysis. These were derived from the Tanga and Amani records. The mean monthly evaporation record for the Lanconi catchment was taken as the average of the records at the two sites since the catchment covered the range of altitudes between the two sites. The mean monthly evaporation record for Mabayani Dam was weighted, on the basis of altitude, towards the Tanga record, since the dam was only 52 m higher than Tanga. Table 2.5 lists the Tanga and Amani records, and those derived for the Lanconi catchment and Mabayani Dam. Figure 2.6 shows the monthly variation in the records.

2.2.5 Reservoir details

Mabayani Dam is 350 m long and up to 19 m deep, retaining a reservoir approximately 5 km long and on average 0.50 km wide. The spillway is an overflow weir located on the left bank of the reservoir about 1 km upstream of the dam. The spillway has a design flood discharge capacity of 1150 m^3s^{-1} at a flow depth of 3.1 m. In order to allow for existing water abstraction rights from the Sigi river downstream of the dam, the required compensation water discharge from the reservoir is 1500 m^3day^{-1} (JBG, 1983; JBG, 1986).

The variation in reservoir area and capacity with stage is tabulated in Table 2.6 derived from JBG (1986). At the spillway crest level of 91.20 m (full supply level) the capacity is 7.7 Mm^3 comprising approximately 1.5 Mm^3 of dead storage and 6.2 Mm^3 live storage. Also shown is the allowance for sedimentation after 20 years (which will be reached in 1998). Sedimentation loss is specified in the MAJI Design Manual (1986) as a loss of 0.5% of the capacity per year. This has been taken off the live storage i.e. after 20 years the capacity will be only 90% of the original. Sedimentation is a severe problem in the region, particularly for such a small dam with such a relatively large inflow, and the 0.5% loss estimate may underestimate the real value by a considerable amount. It is recommended that studies of sediment transport and siltation rates are carried out in order to improve estimates of the rate of decline of the dam capacity.

Table 2.6 Stage-area-volume relationship for Mabayani Dam

Stage (m)	Area (km^2)	Original volume (Mm^3)	20-year volume (Mm^3)
72.0	0.00	0.00	0.00
82.5	0.33	1.47	1.47
83.0	0.37	1.70	1.68
84.0	0.44	2.15	2.09
85.0	0.51	2.63	2.52
86.0	0.60	3.20	3.03
87.0	0.68	3.80	3.57
88.0	0.77	4.63	4.32
89.0	0.89	5.50	5.10
90.0	1.00	6.50	6.00
91.2	1.18	7.70	7.08
92.5	1.37	9.75	8.93

A fairly continuous record of dam water levels between September 1981 and August 1993 were provided (MAJI, 1994), but they were of little direct use since they were not accompanied by any corresponding abstraction and release data. They do however show that the dam was in a virtually continuous state of spill throughout the period.

2.2.6 Rainfall-runoff modelling

As described in section 2.2.2, the available flow series at Lanconi, required to generate the reservoir inflow series, is too short (34 years) to allow a good estimate of reliability of the yield to be made. Consequently, it was necessary to extend the record using the 70 years of catchment average rainfall data available. The available flow series was used to calibrate a rainfall-runoff model, which was then used to reconstruct flows for the 70-year period. This enabled generation of a reservoir inflow series of adequate length.

The rainfall-runoff model used for extension of the flow series was the Pitman monthly model (Pitman, 1973). This model is based on empirical equations to represent surface runoff, soil moisture changes, groundwater infiltration and other processes. Each of these equations contains parameters which have to be evaluated or chosen. The model was originally developed for use in South Africa, but work by Pitman has generalised the model to arid, semi-arid and humid conditions, highlighting the important parameters in each case and enabling estimates of sensible initial values. The model has been applied to a broad range of catchment-types and climate-types throughout southern Africa, and has been found to perform satisfactorily in numerous water resource studies.

The inputs to the model are monthly rainfall and evaporation, and the output is simulated monthly flows. The calibration is done by comparing the observed and simulated mean annual flow (MAR), the mean of the logarithms of the annual flows (mean(logs)) and the standard deviation of these logarithms (sd(logs)) (since the annual totals of runoff generally follow a lognormal distribution). In addition, the seasonal distribution of the monthly flows are compared. Fitting by MAR alone gives too much weight to the accurate prediction of high flows. To give some weight to the prediction of low flows, the fit of mean(logs) should also be examined, whilst sd(logs) is a useful indicator of the variability of the annual flows. All three annual indicators and the comparison of the seasonal distributions were used to fit the model.

22 complete calendar years of monthly flow data were selected from the flow record for calibration of the Pitman model. The parameter values for the best fits of the model obtained are given in Table 2.7 and described in Pitman (1973). Table 2.8 gives the comparison of the annual flows and Figure 2.7 compares the seasonal distribution of flows. It can be seen that the agreement for MAR and mean(logs) is excellent, whilst that for sd(logs) is also good. Examination of the seasonal distribution shows that the model tends to overpredict the high flows, particularly in May and June, and slightly underpredict the low flows, but the lag is perfect. Numerous combinations of model parameters were tried, but none could be found which made a significant improvement, whilst at the same time retaining reasonable agreement in other months and in the annual characteristics.

Table 2.7 Parameter values used in Pitman model for Lanconi

Parameter	Unit	Value
POW	-	3.0
SL	mm	0.0
ST	mm	275.0
FT	mm month^{-1}	30.4
GW	mm month^{-1}	0.0
AI	%	0.0
ZMIN	mm month^{-1}	1500
ZMAX	mm month^{-1}	1500
PI	mm	1.5
TL	months	0.45
GL	months	0.0
R	-	0.5

Table 2.8 Comparison of observed and simulated annual flow characteristics

Measure	Observed flows (Mm^3)	Simulated flows (Mm^3)
MAR	183.230	183.289
mean (logs)	2.203	2.203
sd (logs)	0.248	0.236
MAR (extended series)	-	231.900

A further indication of the fit of the model is given in Figure 2.8 which is a plot of simulated against observed annual runoff. Again, the overall fit is fairly good, and it should be remembered that poor fits are as likely to be due to limitations in the input data as to be the result of inadequacies in the model.

The 70 years of monthly catchment average rainfall data were used as input to the Pitman model to produce a 70-year sequence of simulated flows at Lanconi. Where available, the generated sequence was replaced by the observed flows. This extended flow sequence is given in Table 2.9. The mean of this extended series is 231.90 Mm^3. This compares with 183.29 Mm^3 for the 22-year calibration period, but compares more closely with the mean for the entire 33-year flow record of 219.48 Mm^3. This suggests that the calibration period was an anomalously dry period, or more likely the wet years were incomplete and so were excluded from the calibration.

Having extended the flow series at Lanconi, the next step was to generate the reservoir inflow series. This was done by scaling up the flow at Lanconi to allow for the increase in flow between Lanconi and Mabayani Dam. The scaling factor was based on the product of the ratio of the area of the dam catchment to the area of the gauging station catchment, and the ratio of the average rainfall of the dam catchment to the average rainfall of the gauging station catchment. The results was a 17% increase in flow between Lanconi and the reservoir. However, since the extended flow series was already overestimating the mean annual flow at Lanconi by approximately 5%, a more conservative 10% increase was used i.e. all the flows were scaled up by 10% to derive the actual reservoir inflow series.

Table 2.9 *Extended flow sequence at Lanconi (January 1921 - December 1990)*

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1921	0.32	0.36	0.51	107.60	80.99	19.50	9 02	5 56	3.49	2.56	2 09	1.97	233.97
1922	1.95	1.33	4.70	32.35	145.21	90.38	16 65	8 05	5.48	3.87	7.51	12.26	329 74
1923	13.48	10.06	5.40	89.25	88 54	33.52	15.18	23 86	17 95	7.71	5.99	9 65	320.59
1924	9.50	7.34	6.46	36.10	48.12	26.36	11 53	6 97	4 30	2.54	1.54	1.27	162.03
1925	1.39	3 13	3.94	3.55	4.13	6 03	7 81	8 34	7.95	81.89	110.46	57.33	295 95
1926	18.10	5.61	1.82	2.99	8 60	10 99	7 55	4 42	4.32	5 19	50 76	36 71	157.26
1927	7.54	2.06	2.27	15 43	56 79	37.59	9.68	4 87	4.27	112.41	97.79	66.71	417.41
1928	35.18	6.72	4.14	61.97	105.80	60.22	19.10	9 94	6.38	4.38	53.65	53.92	421.60
1929	21.08	6 24	2 32	4.61	35.41	53 64	30 18	10 91	5.78	5.13	6 05	5 99	167.34
1930	4 35	2.50	3 69	22.82	19 49	7 06	2.81	1 91	2.21	2 83	6.56	10.10	88 33
1931	8 44	5.92	5 80	35.86	142.59	86 60	14 22	5 69	3.98	3 33	4 32	7.78	324.53
1932	7 32	3.54	17.57	76.04	122.93	61.40	11.03	3.88	3.74	3 97	2.76	3.37	317.53
1933	6 47	7.55	5.86	6.41	7.59	5.98	5.68	6 35	5.26	4 15	4.72	7.59	73 61
1934	7 41	3 66	1.70	3.27	51 21	43.81	17 34	9.21	4.82	3.60	3.34	6.22	155 59
1935	6.53	3.56	31.38	44.55	61.24	40 39	14 31	7 95	8.60	8 74	7.93	8.12	243 30
1936	6.31	3.83	2.28	38 94	98.15	94.76	39.00	11.71	10 72	10 56	7.22	5.65	329.13
1937	4.54	2.15	2 56	7.45	38 56	28.21	7 72	3.58	3.02	79.27	66.20	29.37	272.61
1938	14 92	4.49	2.79	62.23	118.86	61.10	12.97	6 28	3.78	15.13	16.79	13.29	332.63
1939	10 24	4.92	1.97	2.36	129.22	96 00	19.65	6 11	4 14	4.38	3.99	3 02	286 20
1940	2.52	2.15	2.52	95 59	132.90	57.04	10 47	6 09	6 58	9.61	9.64	5.60	340.71
1941	2.64	1.15	1.28	20.08	48.68	32.32	11.78	7 10	5.86	4.78	8.26	51.30	195.21
1942	36.84	8.42	3.40	7.64	53.82	38.65	9.70	5 24	3.58	3.11	38.25	32.40	241 05
1943	10.64	5.61	3.79	5.70	30.66	32 51	18 82	11 30	6.09	2.78	3 84	4 40	136 34
1944	2.66	1.25	0.90	51.85	70 47	35.27	15 50	10 92	7.56	16.66	16 66	12 09	241.89
1945	11.42	7.55	3.68	4.56	58.35	43.30	11 37	5.43	3.68	2 77	2.75	3.65	158.51
1946	3.23	1.57	0.54	8.54	57.58	39.39	8.58	4.82	66.86	88 93	39.44	8.75	328 23
1947	2.85	1.20	1.60	72.67	134.71	67.43	11 89	4.10	5.31	6.91	9.00	9.50	327.17
1948	5.75	2.00	1.06	17.62	46 00	32 12	14 48	9.56	5.49	4.31	5.95	9.38	153.72
1949	8.72	4.22	1.40	15.01	39.71	26 24	12 77	11.67	7.71	3.75	1.61	4.33	137.34
1950	5.33	2.52	5 30	65.92	55.17	18.47	9 05	7.20	7.35	6 87	5.01	3 99	192 18
1951	4 12	3 35	1 61	3.35	110.33	76 63	12.89	4.92	2.92	28.20	73.39	100 21	422 12
1952	47.94	7 40	1 88	1 85	4 90	8 35	7.39	4.19	3.07	5.24	11.16	12.13	115 50
1953	7 77	3 49	2.27	4.54	48 60	35 29	8.58	7.17	10.37	53 93	39.26	11.68	232.95
1954	5 41	3.38	3 79	7.05	31 78	23 76	7 43	4 87	4.02	3 28	3 90	4.30	102 97
1955	3 53	2 76	2.94	33.56	91.78	61 12	18 77	7.66	3.16	1 49	1.24	3.21	231 22
1956	5 08	3 56	1.62	3.18	9 09	11 86	8.50	4 16	1.90	1 24	2.55	4.62	57.36
1957	8 82	8 95	5.78	44.89	90.60	18 63	14.76	9 89	9.90	12.55	22.71	52.50	299.98
1958	13.77	11 03	16.43	23.84	27.38	34 33	19 08	21 56	17.86	16 80	7.30	15.81	225 19
1959	10 33	5.33	8.84	21.64	43.75	6.21	6 44	12 22	5.21	4.97	4.46	3.58	132.98
1960	2.60	1.23	9.35	68 05	30 82	14.80	9.08	6 68	4.68	7.37	4.31	3 20	162.17
1961	2.31	5.18	5 36	5.21	9 67	4.39	16.58	6 59	11.75	54.99	105.72	43.16	270.91
1962	34 11	11 80	25.08	12.23	9 40	6 34	6.82	6 14	5.16	3 82	6.18	8 44	135 52
1963	5 80	5.05	11.26	39.11	29.59	12.71	11.85	8 59	6 85	7.44	75.37	55.11	268.73
1964	12 38	13.51	12.25	27 52	19.57	13 13	3 45	1 18	0.79	8.93	3.07	3.27	119 05
1965	4.12	1.49	1.97	8 75	23 60	8 83	7.74	8 62	5.02	23 60	53.54	24.91	172.39
1966	10.04	6.55	10 93	30 64	55.80	69.26	28 53	14 42	6.12	5.16	9.87	4.50	251.82
1967	1.68	1.63	2.68	14.49	48.80	17.37	13 10	12 24	44.33	109.68	127.30	24 61	418 11
1968	14.50	7.57	32.56	57.33	64.22	121.38	18 31	10 43	5.09	10 56	81.48	38 31	461.74
1969	3.58	2.86	4.29	3.08	4.12	11.05	7 67	15 92	9.97	56.63	55 68	26.88	201.71
1970	12.47	8.23	12.44	15.01	19.81	8.41	5.95	4.58	5.70	3 60	1.96	31.50	129.66
1971	3.90	2.35	5.45	13.56	12.97	10.15	9 45	7.08	4.84	3 38	1.83	3.10	78 06
1972	4.28	2.60	2.81	15 41	65.82	22 05	11.53	6.70	14.70	72 44	156.84	45.71	420.69
1973	23 06	9.60	6.00	14 07	42.80	12.73	8.68	7.56	4.88	3.05	2.66	5.68	140.77
1974	3.10	1.99	1.68	4 62	6.77	6 91	21.09	5.70	3.53	3 31	4.42	1.44	64.54
1975	3.42	0.44	2.03	9.46	10.77	6 09	5.46	3.73	7.33	4.09	2.78	3.76	59.36
1976	1 29	2.49	0.58	10.15	11.58	2.20	0.92	0.64	2.23	1.41	1.07	0.27	34.83
1977	4.15	2.26	2.91	9.04	5 99	3 34	2.31	7.57	16.22	40 96	62.60	35.33	192 68
1978	73 79	13.07	3.27	99.28	68.81	21 93	9.16	4.46	2.23	1.26	66.04	46.69	411.99
1979	13.48	25.89	20.74	66.21	159.05	125.29	38.62	19.31	17.93	12 94	17.29	8.58	523 33
1980	7.75	5.27	3.20	11.68	24.78	6.79	8.84	13.51	14.50	65 90	14.18	26.14	202 54
1981	5 60	2.61	8.36	19.66	24.20	8 65	6.41	6.71	6.13	29 97	9.32	16.56	146 38
1982	6 91	3.14	2.54	3.92	61.71	19.27	32.03	20.75	19.43	95 03	63.67	50.24	378 64
1983	14 88	8.11	7.64	7 45	45 58	21 05	11.14	8.21	6.74	4 71	3.82	4.39	143 72
1984	2 61	1.09	1.75	41 68	31.74	17 51	19.90	9.56	7.19	13 26	74.80	33.26	254 35
1985	19.54	16 35	9.68	19 98	67 92	17 40	15.48	10.79	8.38	16 38	25.01	50.62	277 53
1986	15.59	5.99	6.49	77.01	115.19	53 24	21.20	13 63	8.53	6 93	7.88	13.25	344 93
1987	5.62	1.50	3.36	5.24	62 66	10 55	7.30	28.35	8.36	8 13	4.59	3.00	148 66
1988	3.49	1.13	1.89	8 65	4 78	8 16	4 56	4.21	28.03	10 59	21.31	20 40	117.20
1989	21.29	7.70	6.48	23 12	37 92	33 80	9 53	3 86	5.77	12 47	14.37	10 19	186.50
1990	12.71	6.48	23.99	103 41	64 38	17 77	10.20	5.26	2.79	3 40	7.77	25 83	283.99
Mean	10.50	5.10	6.10	28 69	54 15	32 50	12.73	8 41	6.43	19 16	26.47	19.52	231.90

2.2.7 Reservoir yield analysis

Estimates of the yield which can be supplied for various return periods of failure are required for the existing reservoir capacity. The probabilities of failure adopted were 1, 2, 5, 10 and 20%, equating to return periods of failure of 100, 50, 20, 10 and 5 years respectively. For the purpose of this study, the probability of failure is defined as a percentage, on an annual basis, and is calculated using all years during which a failure occurred in one or more months. This basis is not ideal as it does not incorporate any measure of the duration of each failure which corresponds to the severity of the drought. However, it is the measure used in most storage-yield analyses, and no readily accepted alternative has been established.

A large number of reservoir yield design procedures are available. The current study assessed reservoir yield by the failure rate method. For this method, the starting month must be a wet month so that the dry season is not split, and the wettest month of May was used. A monthly reservoir water balance is carried out and the number of annual failures of any duration is noted. This is then expressed as a percentage of the total number of years to get the probability of failure.

The failure rate method was used with the 70 years of monthly inflow data, the 70 years of rainfall at the dam and the mean monthly evaporations. A range of demands from the original design yield of 26000 m^3day^{-1} up to the JBG (1983) estimate of 60000 m^3day^{-1}, and then up to about quarter of the mean annual runoff (130000 m^3day^{-1}) were examined, for both the original reservoir and for the smaller capacity reservoir following 20 years sedimentation. The results are plotted in Figure 2.9, which shows yield after compensation release (of 1500 m^3day^{-1}) against probability of failure for the two capacities. For the original reservoir, note the constant rate of failure (1.5%) from initial failure at 68500 m^3day^{-1} to 104500 m^3day^{-1}; a similar phenomenon occurs for the 20-year silted reservoir. This rate of failure corresponds to a single failure (1983/84) in the 70 years of simulation, over a large range of demands. The rarity of such a failure justifies drawing the yield curve in at the higher end of the demand range i.e. given another 30 years of data, this event would most probably still dominate as its return period is probably nearer 100 years. The yields for the return periods of interest have been abstracted and are listed in Table 2.10.

Table 2.10 Results of reservoir yield analysis for Mabayani Dam

Return period of failure (yr)	Daily yield (10^3 m^3) Original capacity	Daily yield (10^3 m^3) 20-year capacity
5	132	126
10	120	114
20	110	105
50	102	97
100	100	93

2.2.8 Conclusions

The final estimates of the yield of Mabayani Dam near Tanga are based on Pitman model extension of the flow series at Lanconi using the long-term rainfall series at Amani. The fit of the Pitman model was reasonably good, producing a long sequence of flows at Lanconi which were scaled up to provide the reservoir inflow series. Since Mabayani Dam has been in operation since 1978, it should be possible to compare the results presented to the actual performance of the dam, given water level, abstraction and release records. The two most serious current threats to the yield of Mabayani Dam are pollution and siltation.

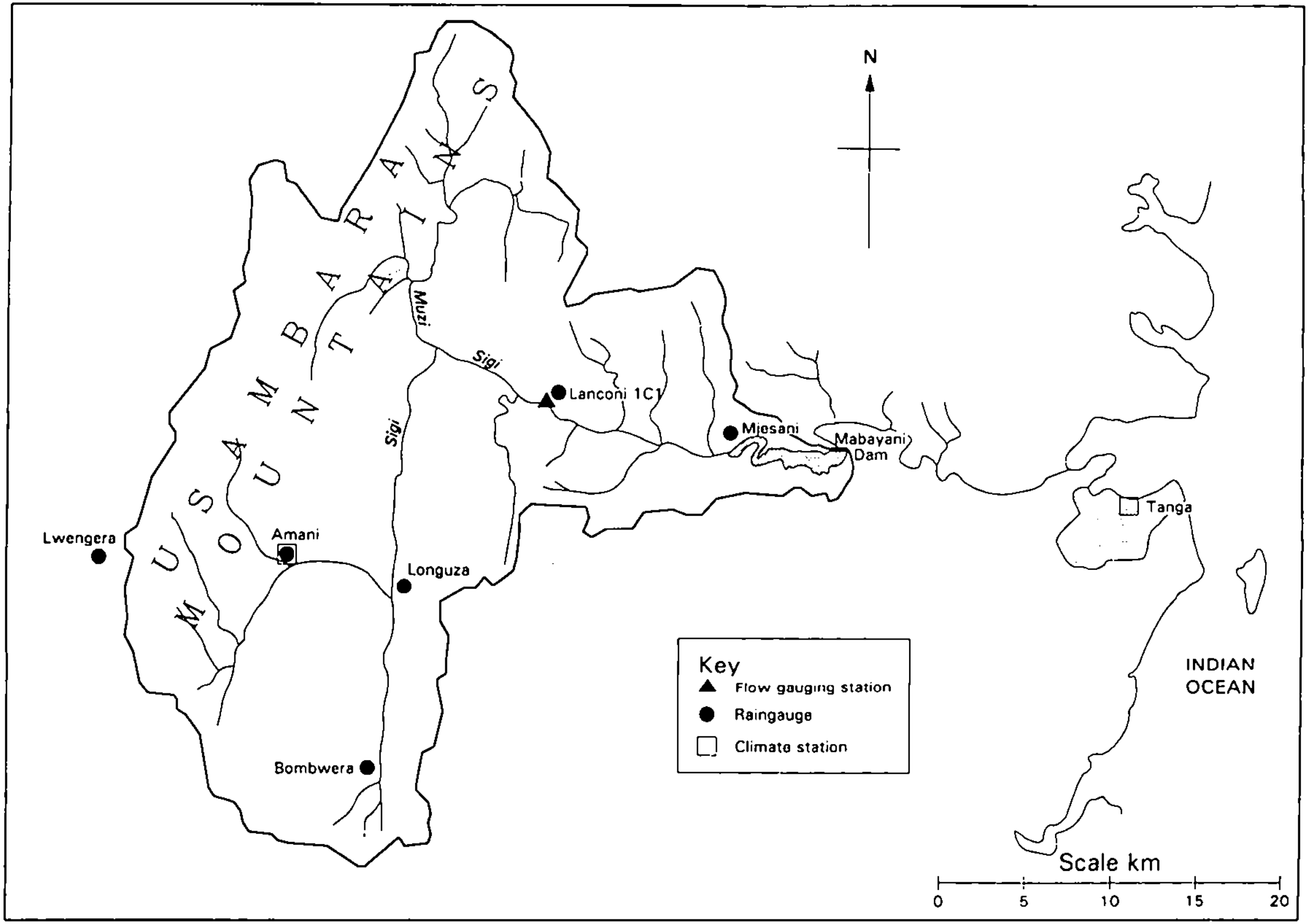

Figure 2.1 Plan of Mabayani Dam catchment showing locations of gauges

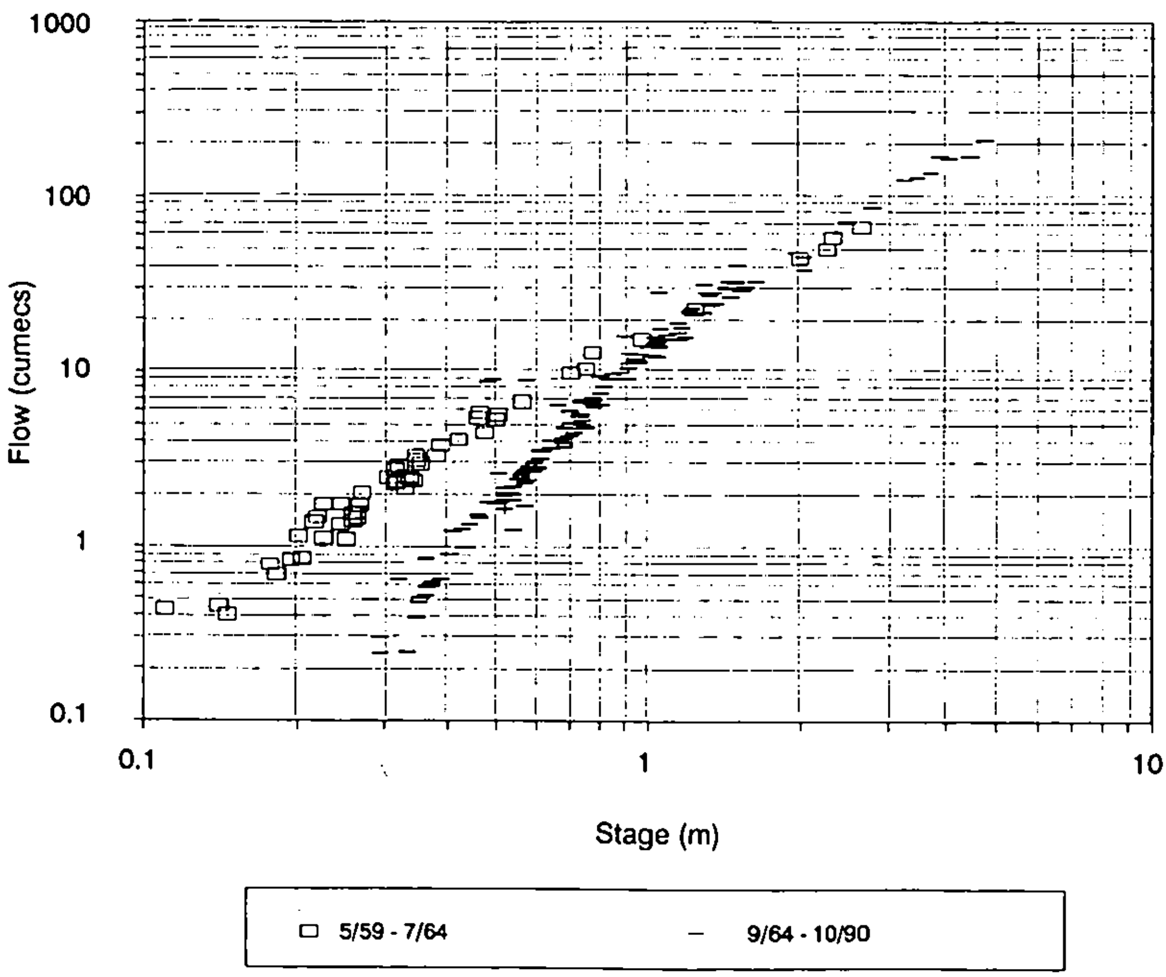

Figure 2.2 *Current meter measurements for Sigi at Laconi*

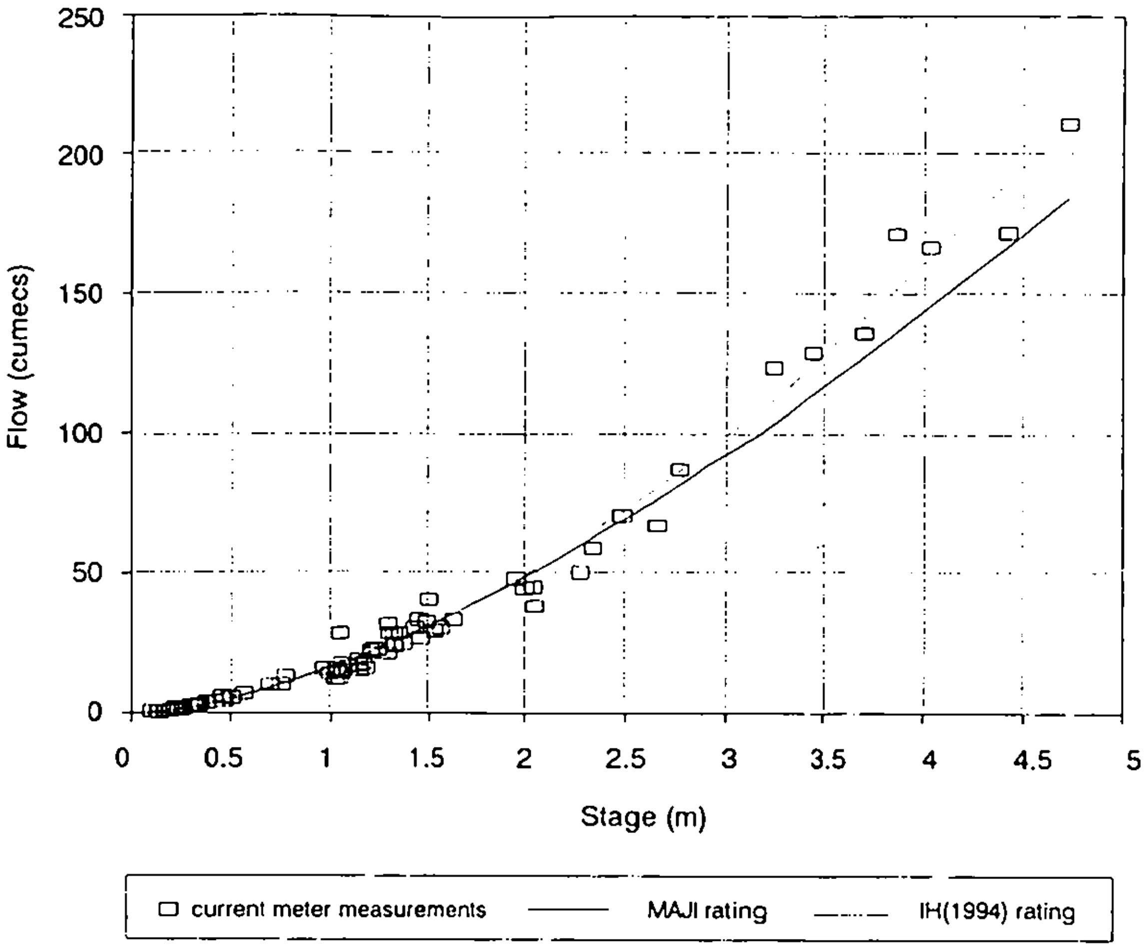

Figure 2.3a *Rating equation for Sigi at Laconi up to 09/07/64*

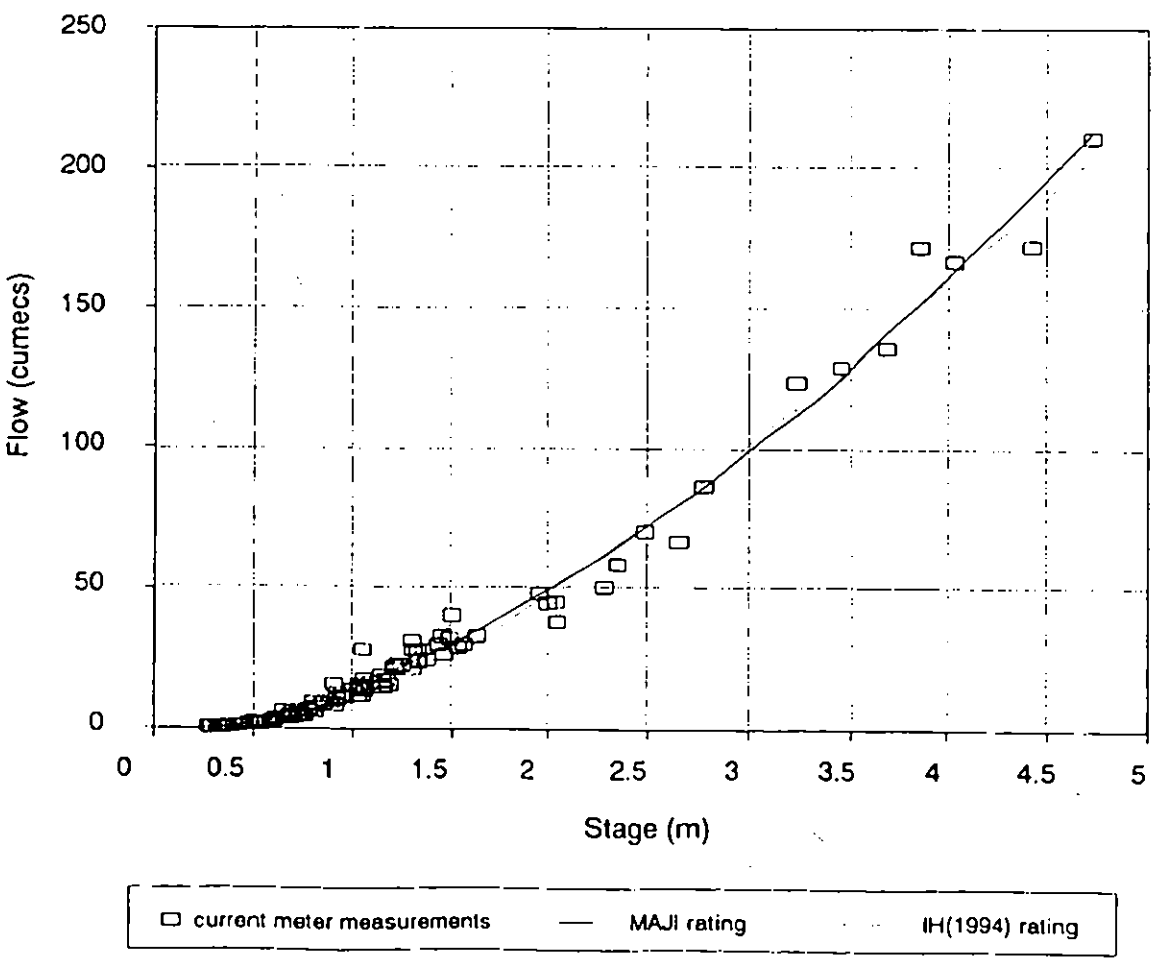

Figure 2.3b *Rating equation for Sigi at Laconi from 10/07/64*

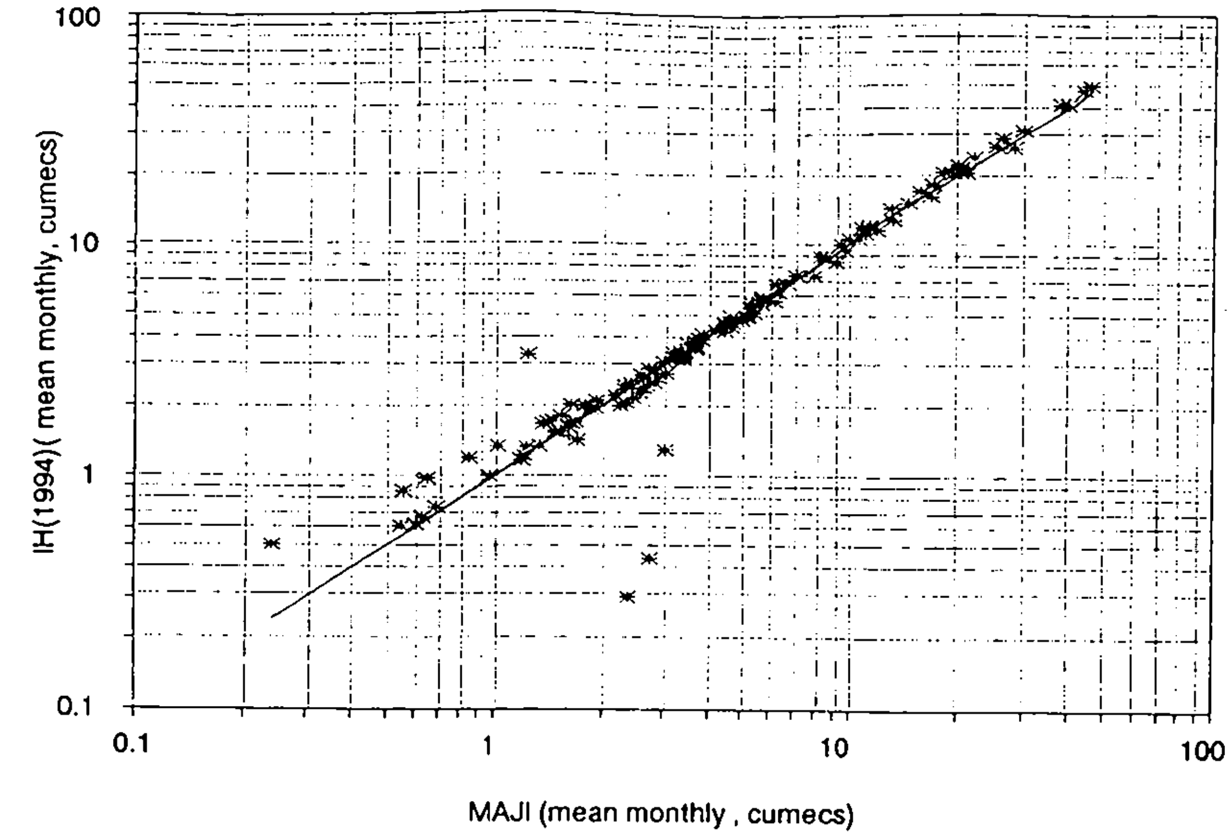

Figure 2.4a *Comparison of IH (1994) and published MAJI flows for Sigi at Laconi*

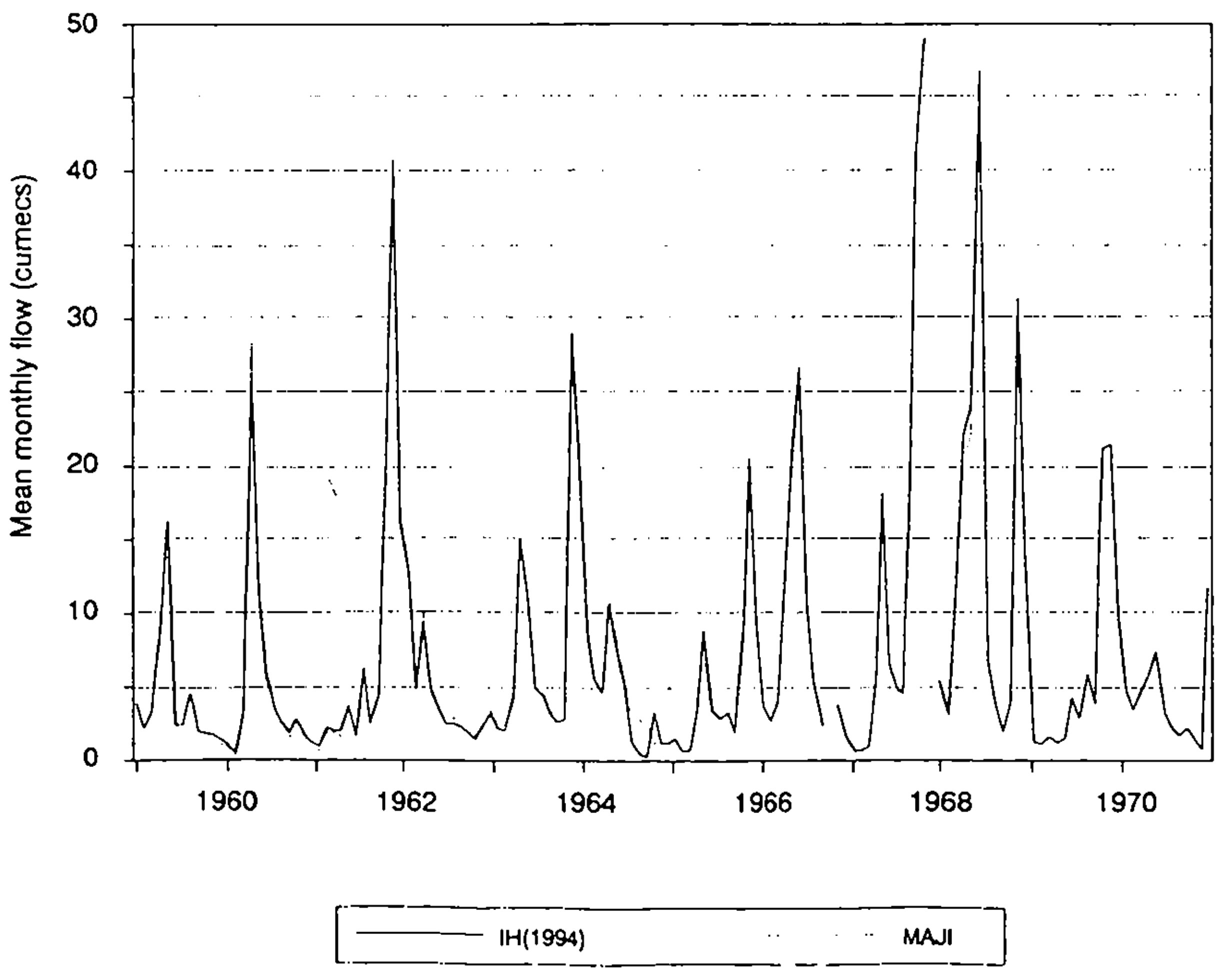

Figure 2.4b *Comparison of IH(1994) and published MAJI flows for Sigi at Lanconi*

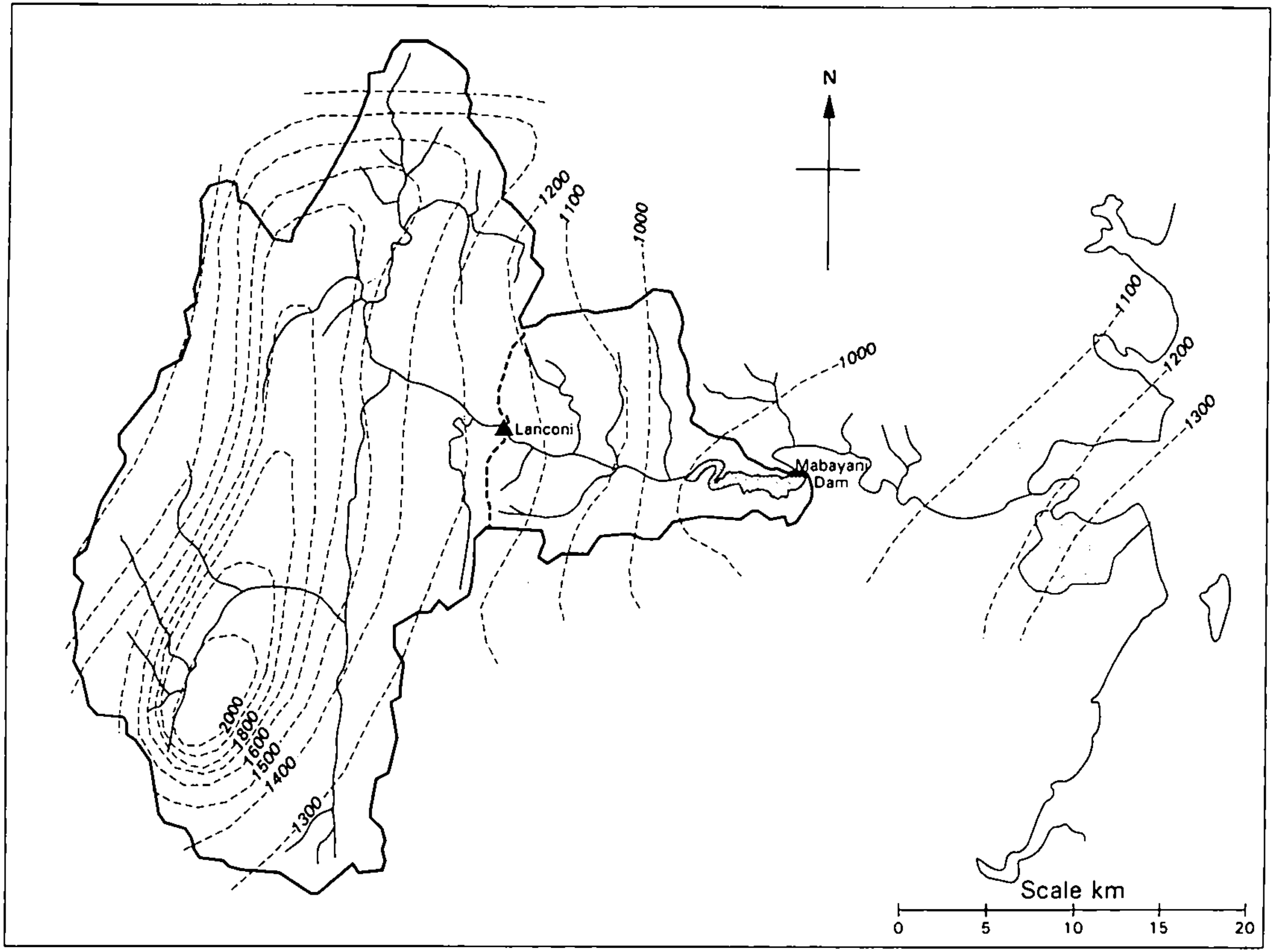

Figure 2.5 Rainfall isohyets (mm) in Tanga region

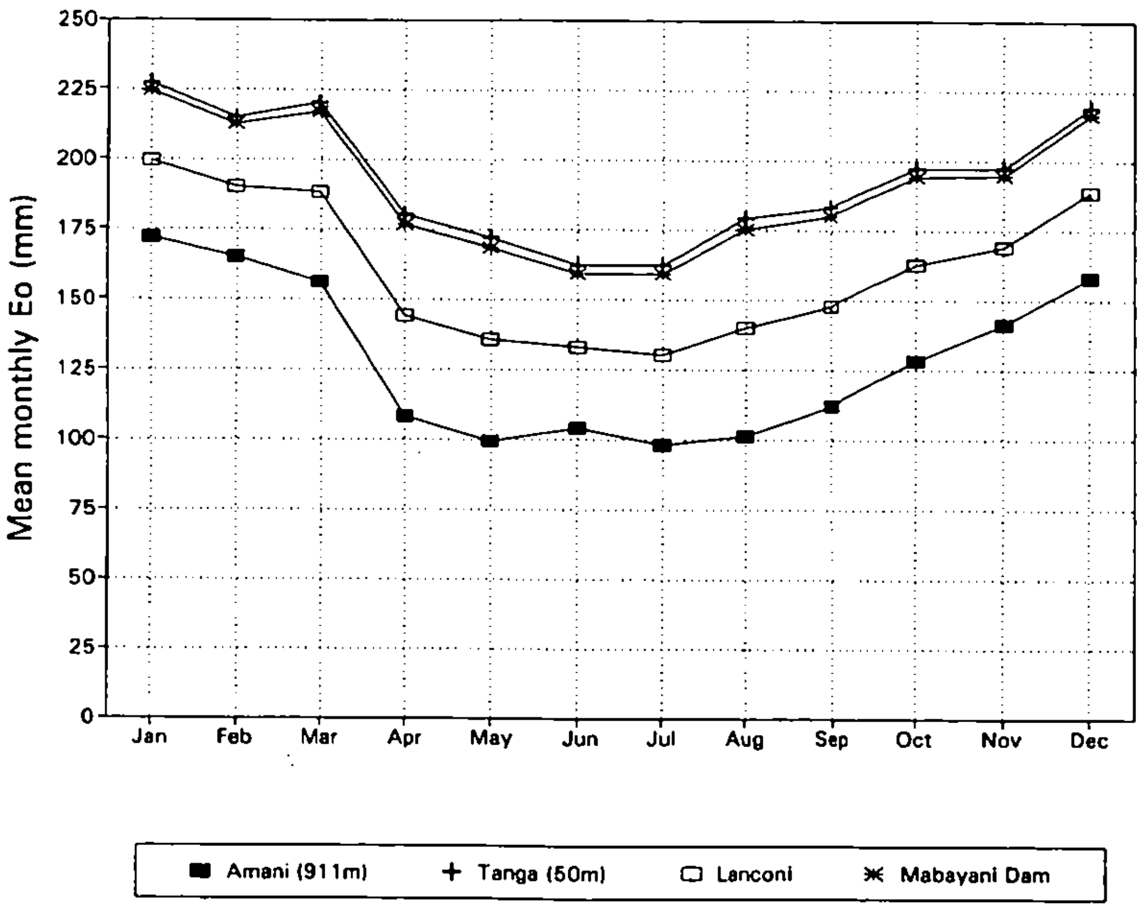

Figure 2.6 Monthly variation in open water evaporation

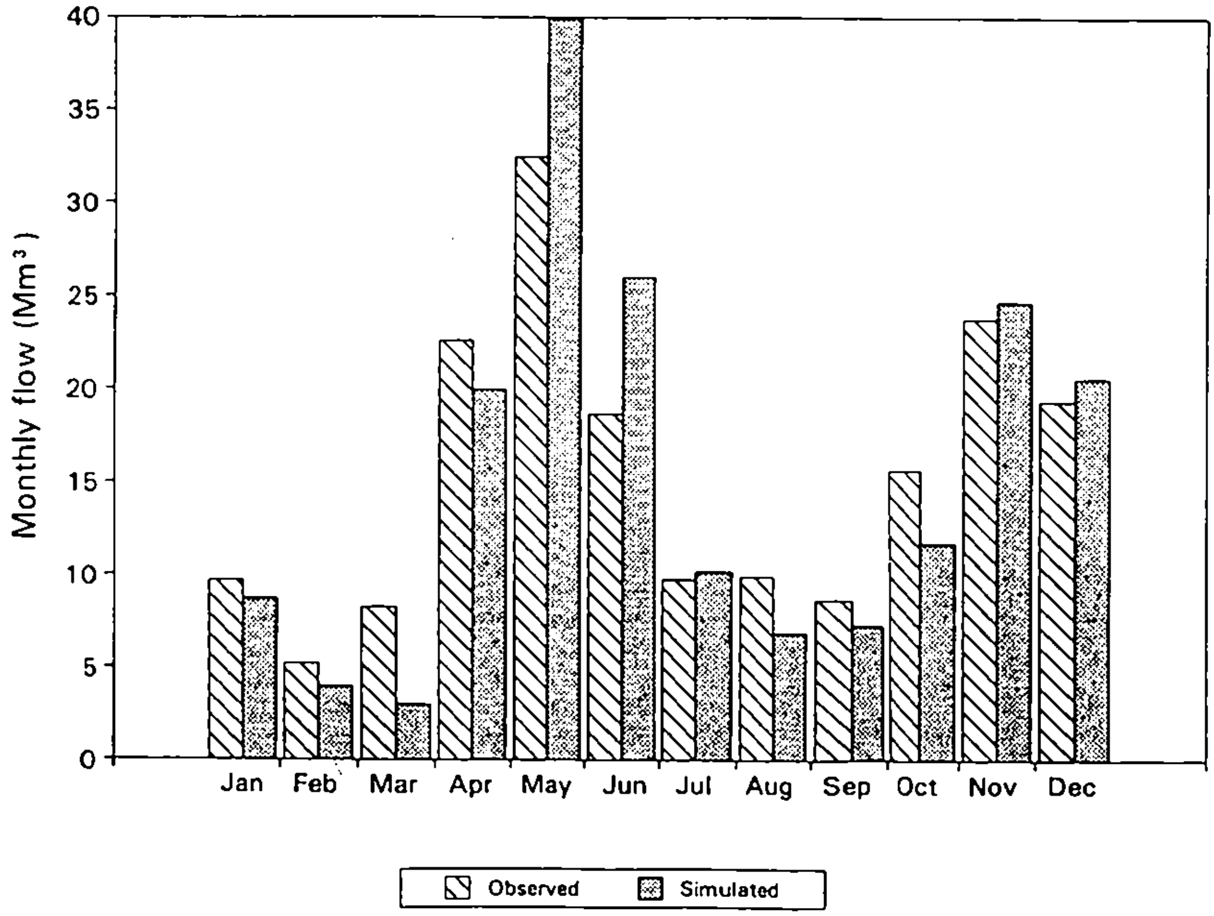

Figure 2.7 Comparison of seasonal distribution of observed and simulated flows from Pitman model calibration for Sigi at Lanconi

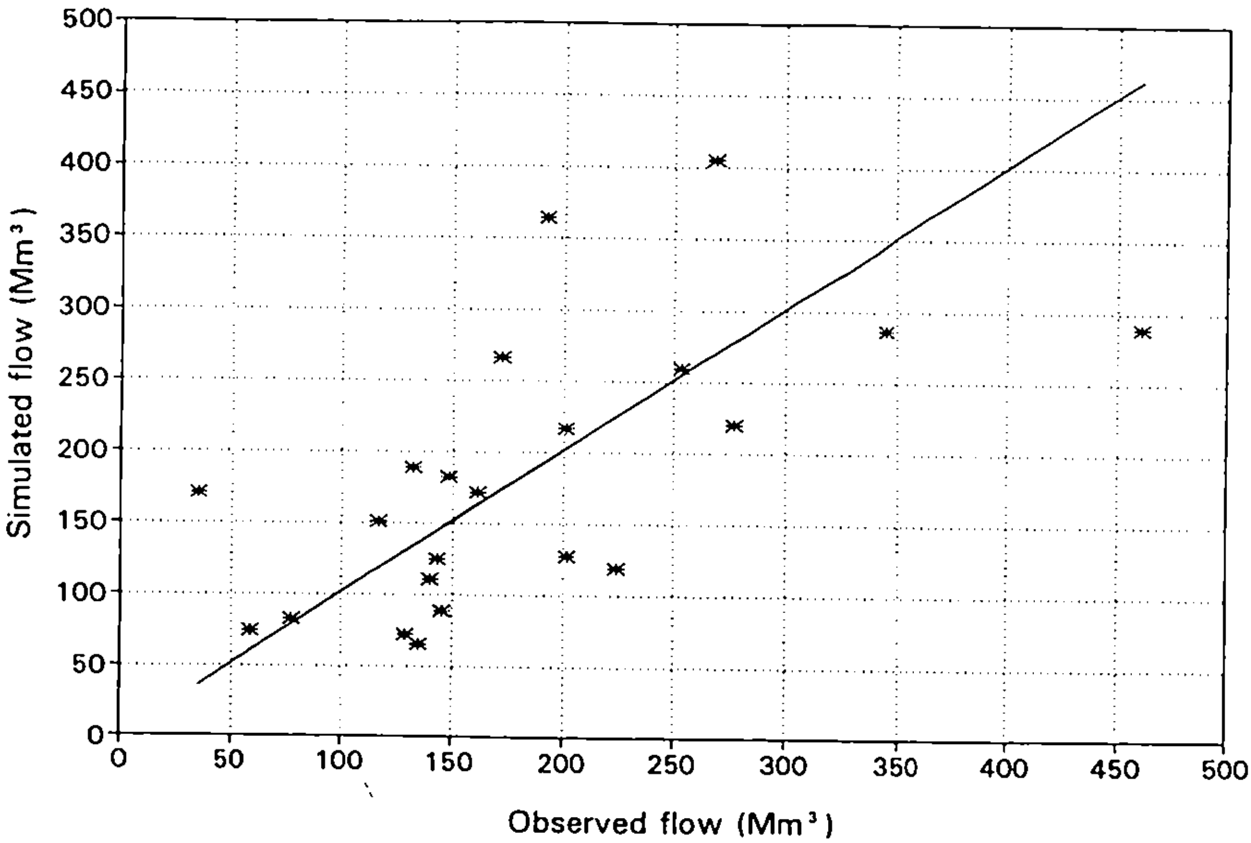

Figure 2.8 Observed and simulated annual flows from Pitman model calibration for Sigi at Lanconi

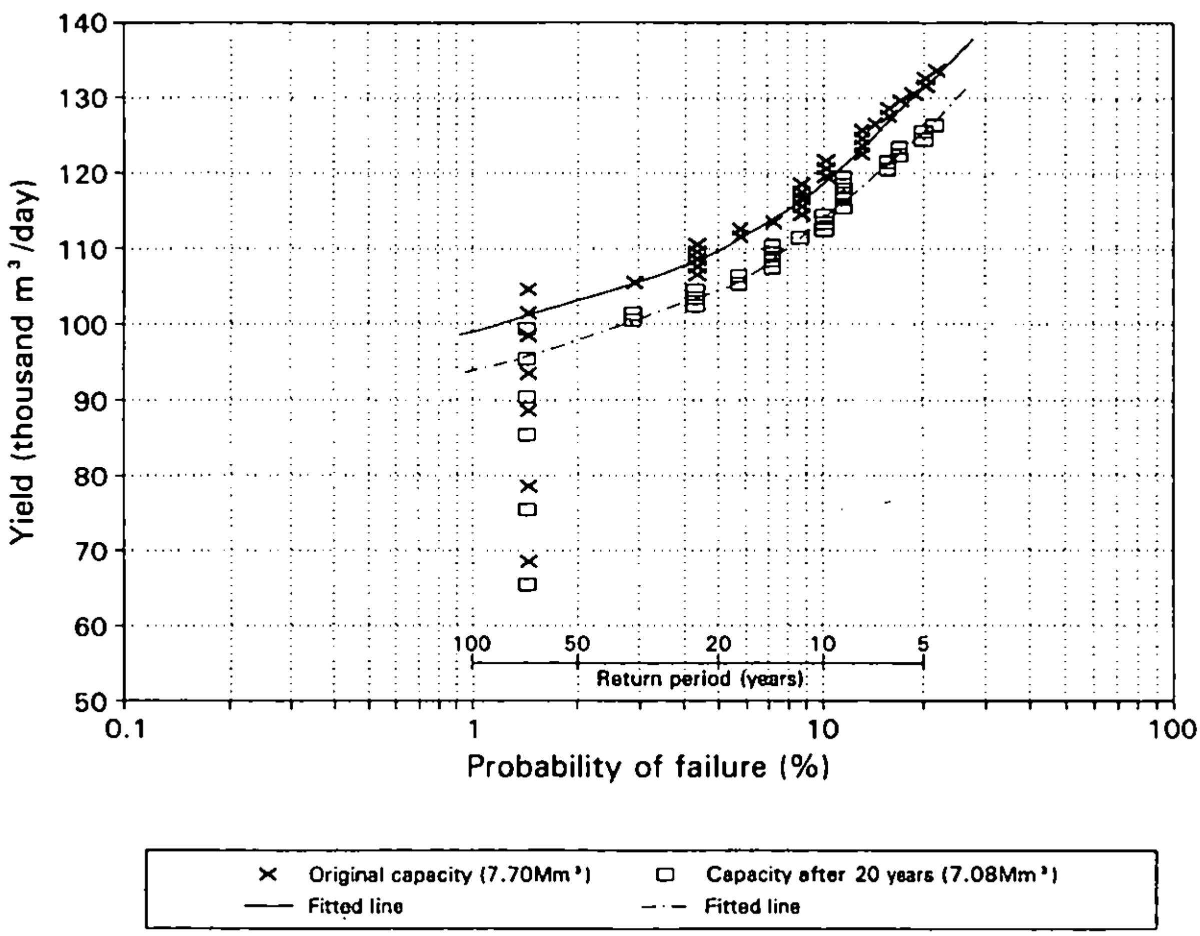

Figure 2.9 Results of reservoir yield analysis for Mabayani Dam after compensation flow release of 1500m³/day

3. Morogoro

3.1 BACKGROUND

Morogoro is situated inland on the foothills of the Uluguru Mountains, about 200 km west of Dar-Es-Salaam, as shown in Figure 1.1. The town is well connected by road and rail links to the rest of the country and has heavy through-traffic between the principal towns of Dar-Es-Salaam, Dodoma, Iringa and Mbeya. Hence, as well as the more traditional industries of manufacturing and small-scale agriculture, there are quite large commercial and tourism sectors. The town is at an altitude of about 500 m, and though part lies on the lower slopes of the mountains, most of the town is on the valley floor and at risk from flooding during the wet season. The geology comprises ancient, heavily weathered metamorphic rocks which give rise to well-drained sandy, clayey and loamy soils, though a high permanent groundwater table creates swamps in low-lying areas. The humid equatorial climate of the region is influenced by the surrounding mountains. The average annual rainfall is around 900 mm, falling mainly in the April to June wet season, but also between October and December.

The Morogoro water supply system dates back to the early part of this century when the Morogoro river, which flows in a north-easterly direction off the Uluguru Mountains, was used as the source. However, following a proposal by JBG (1973), Gibb conducted a feasibility study to investigate development of the nearby Ngerengere river as the primary source (Gibb, 1975), and in 1985 Mindu Dam, on the Ngerengere river about 6 km south-west of Morogoro, was completed (Gibb, 1986).

The hydrology of the Ngerengere river has been reviewed extensively in reports preceding the construction of Mindu Dam (JBG, 1973; Gibb, 1976; Gibb, 1980). In particular, Gibb (1980) utilised all available hydrological data in order to do a comprehensive review of the design flood for Mindu Dam by the unit hydrograph method. The original design was derived from an examination of all notable flood events recorded in the hydrological yearbooks for Tanzania, from which a limiting line was drawn defining extreme flood flow against catchment area. The design yield of the reservoir at Mindu Dam was estimated at 58000 m^3day^{-1}, with an option for a second stage raising of the dam by 2.5 m to increase the potential yield to around 68000 m^3day^{-1}. The dam is threatened primarily by severe sedimentation, caused by intense agricultural activities upstream and in the headwaters.

Poor catchment management practices were recognised as a potential problem in Morogoro in the early part of this century. In 1945 the Uluguru Land Usage Scheme was launched, with the aim of promoting methods to reduce the advanced state of soil erosion and deterioration of water supplies, but was abandoned in 1953 following social and political repercussions. JBG (1973) proposes sediment transport rates which could have disastrous effects for small reservoirs; the possibility of a reservoir filling up in a very short time cannot be discarded.

The original source, the Morogoro river, is of marginal importance for future water supply as insufficient water exists in the river to satisfy demand by run-of-river abstraction. It is reported to be able to reliably supply up to 2275 m^3day^{-1} at the Mambogo intake, with even this subject to short duration failures (Gibb, 1976). The river water supply is supplemented by three spring source intakes: two longstanding ones, at Kibwe and Kigurunyembe, believed to be able to yield about 1000 m^3day^{-1} between them (COWIConsult/Interconsult, 198?), and a recently developed one at Vituli, of unknown yield.

Looking to the future, with all nearby river and spring sources utilised and the potential for expansion of groundwater abstraction via boreholes low, planners will surely have to look further afield. COWIConsult/Interconsult (198?) refer to discussions regarding the abstraction of water from the Wami and Mgeta rivers located, respectively, 50 km to the north and 40 km to the south-west of Morogoro.

3.2 YIELD ASSESSMENT FOR MINDU DAM

3.2.1 The Ngerengere catchment

The Mindu Dam catchment lies to the north-west of the Uluguru mountains, and varies in altitude from 500 m in the valley bottom to 2000 m on the watershed. The catchment area at Mindu Dam is 303 km^2. The upper reaches of the catchment are steeply sloping and are dissected by numerous water courses which combine to form the 5 main rivers flowing into the reservoir (Figure 3.1). The main river is the Ngerengere river which was gauged at Konga where the catchment area is 20.70 km^2. Downstream of the dam the Ngerengere river ultimately joins the Ruvu river which drains into the Indian Ocean north of Dar-Es-Salaam. The upper reaches of the catchment are thickly wooded but cultivation on the lower slopes is extending upwards pushing back the forest boundary and contributing to the natural erosion of soils; sheetwash is a characteristic feature, indicative of the comparatively high runoff that can be expected from such cultivated slopes. The annual average rainfall of the catchment varies from around 700 mm in the valley bottom, up to 3000 mm on the watershed.

The design yield of the reservoir at Mindu Dam was estimated at 58000 m^3day^{-1}, expected to decrease to 43000 m^3day^{-1} after 20 years reservoir sedimentation. This has to support a compensation flow release of 16000 m^3day^{-1},as well as contribute to the water supply. An option for a second stage raising of the dam by 2.5 m to increase the yield by 11000 m^3day^{-1} is under discussion. The aim of this study was to assess the potential and 20-year yields of Mindu Dam for various levels up to the maximum proposed (Gibb, 1986).

3.2.2 Flow data

There are several former flow gauging stations in the Mindu catchment and along the Ngerengere river in particular. Table 3.1 gives details of the gauges and available records.

Table 3.1 *Details of flow gauging stations for Mindu Dam*

Gauge No.	Name	Area (km^2)	Period of record	No. of years
1HA6	Ngerengere at Kihonda	461.0	1950-1959	10
1HA7	Mlali at Mlali	18.1	1953-1959	7
1HA9/9A	Ngerengere at Konga	20.7	1954-1988	25
1HA10	Mgera at Mgera	15.5	1954-1959	6

Flow data for the Ngerengere at Konga were provided by the Ministry of Water, Energy and

Minerals (MAJI) in the form of daily, and sometime sub-daily, stage values from 08/11/62. Before this date, the station was a little upstream of its present location. MAJI also provided current meter measurements from November 1962. Monthly flow data for the early part of the Konga record and for the other sites were abstracted from the Hydrological Yearbooks as no computerised data were available at MAJI. Of the total catchment area of 303 km² at Mindu Dam, 169 km² is contributed by the Mlali river, gauged at Mlali in the south-west part of the catchment. The river discharges into an area of seasonal swamps a few km upstream of the reservoir, and comparisons of flow volumes from the catchments now flowing into the reservoir and Kihonda suggest that the Mlali makes a disproportionately small contribution to the flow in the Ngerengere. In the dry season, the contribution may be nil due to evaporation losses from the swamps and groundwater recharge, and in the wet season, any flood peak will be reduced by attenuation in the swamps (Gibb, 1980). Therefore, the effective catchment area of Mindu Dam is only 134 km².

Figure 3.2 shows all the current meter measurements provided at Konga. There is no indication of a switch in the rating at any time since the station was re-established. Some of the current meter measurements were omitted from the analysis because they were believed to be inaccurate; those omitted are shown circled in Figure 3.2. The rating equation developed by IH was:

For the period from 01/11/62:

$$Q = 19.787(h + 0.123)^{2.800} \qquad hmax = 0.22 \text{ m}$$
$$Q = 7.463(h - 0.005)^{1.300}$$

This rating is shown in Figure 3.3. Following conversion of the stage data into flow using the IH(1994) rating, mean monthly flow values were abstracted. Figures 3.4a and 3.4b compare these mean monthly flow values with the limited record published in the Hydrological Yearbooks, and show the two series to agree well, except at very low flows where the IH(1994) values are higher. Again, since it is the overall monthly volumes that are of interest in reservoir yield analysis, the flow record derived by IH was considered acceptable for the current study.

In this study, an attempt was made to use the flow records at Konga, Mgera and Kihonda to generate the inflow series to Mindu Dam. Since none of the records is particularly long, the flow records were extended using longer-term rainfall data. This is described in section 3.2.6.

3.2.3 Rainfall data

There are 16 potentially useful raingauges on or near the Mindu Dam catchment, as shown in Figure 3.1. Table 3.2 gives details of the gauges and the records collected from each gauge. The rainfall data were collected as monthly computerised totals from the Ministry of Water, Energy and Minerals; time did not permit any checking of the raw data to be carried out. Only the raingauge at Morogoro Agricultural College near the dam has a particularly long record. It has a nearly unbroken 64 years of monthly data from 1925, and no trends are apparent on a cumulative mass plot. The other gauges, situated at higher altitudes and on the watershed, have shorter records and missing periods are common.

Table 3.2   *Details of raingauges for Mindu Dam*

Gauge No.	Name	Altitude (m)	Period of record	No. of years
963700	Morogoro AC	500	1905-1990	85
963702	Tungi	500	1932-1989	57
963717	Melela	580	1938-1966	28
963725	Tangeni	640	1940-1988	48
963745	Mondo	1120	1954-1989	35
963746	Morningside	1450	1954-1989	35
963747	Howbe	740	1954-1990	36
963748	Luhungo	880	1954-1989	35
963749	Kwanderwa	880	1954-1989	35
963751	Mlali	590	1956-1989	33
963752	Morogoro WD	510	1956-1989	33
963754	Mlali IS	610	1957-1976	19
963762	Morogoro TT	610	1964-1973	9
963770	Kihonda	580	1967-1989	22
963776	Morogoro MS	530	1970-1989	19
973716	Mizugu Mgeta	1100	1951-1986	35

To extend the flow series at Kihonda and the catchments upstream of Mindu Dam, and thereby enable a long series of reservoir inflows to be generated, it was necessary to have monthly catchment rainfall figures for both the individual catchments and the dam catchment. Long series of monthly rainfalls at the dam site itself were also required. The short record lengths at 15 of the 16 gauges prevented use of a method such as Theissen polygons to calculate the long series of catchment average rainfalls, since the short records themselves would have to be extended first. Table 3.3 shows the correlation coefficients between the monthly totals at the shorter-term raingauges and at Morogoro AC for periods of overlap.

Table 3.3   *Correlation coefficients for monthly rainfall between Morogoro AC and other stations*

Gauge	Correlation coefficient
Tungi	0.71
Melela	0.81
Tangeni	0.81
Mondo	0.73
Morningside	0.77
Howbe	0.75
Luhungo	0.40
Kwanderwa	0.84
Mlali	0.75
Morogoro WD	0.88
Mlali IS	0.76
Morogoro TT	0.83
Kihonda	0.69
Morogoro MS	0.89
Mizugu Mgeta	0.75

These correlation coefficients indicate that the stations may not be necessarily receiving rainfall from the same storms, but that the long-term pattern of rainfall at each station is similar. The lower coefficients e.g. Luhungo, reflect those gauges which showed trends or changes in slope when plotted against Morogoro AC in a double mass plot. The gaps in the Morogoro AC record were infilled by regression with the Morogoro WD record ($R^2=0.77$). Gibb (1980) provide an isohyetal map of the area, reproduced here as Figure 3.5. Some simple checks ensured that the average annual rainfall totals at each of the raingauges put the gauge in the right band on the map. The isohyetal method was used to determine the catchment average rainfall total for each area. The results are tabulated in Table 3.4. The ratio of the catchment average rainfall total to the average annual rainfall at Morogoro AC (888 mm) was applied to the 64-year Morogoro AC record to derive the long-term catchment average rainfall series for each area.

Table 3.4 Catchment average rainfall totals for sites around Mindu Dam

Site	Catchment rainfall (mm)
Kihonda catchment	993 (1040)*
Mlali catchment	1255
Konga catchment	2066
Mgera catchment	1490
Mindu catchment	1378 (1120)*
Mindu Dam	755

* Figures in brackets give catchment rainfall when area upstream of swamp is included

3.2.4 Climate data

A comprehensive study of potential evaporation in Tanzania (Woodhead, 1968) concluded that of the various evaporation estimates available, the Penman estimate of potential evaporation (Penman, 1948) should be regarded as the most suitable evaluation of open water evaporation for tropical East Africa. Unfortunately, few of the meteorological stations in Tanzania were equipped to measure all the variables necessary for the computation of open water evaporation. The report describes the derivation and application of the various techniques developed for assessment of these unobserved parameters, and presents results for 57 sites, including Morogoro, using data from the early 1940s to 1964.

As these open water evaporation estimates are some 25 years old, attempts were made to try and collect some more recent meteorological data from which to derive better estimates. The nearest current meteorological station to Mindu Dam is Morogoro, and a computerised record of Penman evaporation data was provided by the Ministry of Water, Energy and Minerals for the period 1971 to 1989; the early part of this record was fragmentary, but a continuous series from 1981 to 1988 was available. Because evaporation is a very conservative variable which changes little from year to year, taking the mean of the individual monthly totals provides a reasonable method for estimating long-term annual evaporation, and this is what was done.

The evaporation figures required for analysis are mean monthly totals for both the formerly gauged catchments for use in flow record extension, and for the reservoir at Mindu Dam for use in the yield analysis. These were all taken as the mean monthly values from the Morogoro record. Table 3.5 lists the Morogoro record from 1981 to 1988 together with the mean monthly values, and the 1968 published value for comparison, and Figure 3.6 shows the monthly variation in the records.

Table 3.5 Open water evaporation figures (mm)

Site	Jan	Feb	Mar	Apr	May	Jun
1968	173.0	159.0	167.0	126.0	111.0	106.0
1981	186.0	209.1	217.0	81.0	108.5	93.0
1982	238.7	194.9	241.8	141.0	96.1	93.0
1983	139.5	163.9	151.9	114.0	80.6	81.0
1984	133.3	166.7	176.7	93.0	96.1	84.0
1985	201.5	138.4	179.8	105.0	93.0	99.0
1986	151.9	183.6	133.3	93.0	89.9	87.0
1987	173.6	172.3	182.9	117.0	89.9	84.0
1988	223.2	248.6	220.1	123.0	105.4	96.0
1981-88	181.0	184.7	187.9	108.4	94.9	89.6

Site	Jul	Aug	Sep	Oct	Nov	Dec	Total
1968	112.0	126.0	146.0	179.0	176.0	179.0	1760.0
1981	89.9	96.1	159.0	173.6	114.0	114.7	1641.9
1982	93.0	136.4	144.0	139.5	210.0	133.3	1861.7
1983	116.6	96.1	174.0	182.9	225.0	238.7	1759.2
1984	99.2	74.4	177.0	189.1	159.0	198.4	1646.9
1985	99.2	130.2	168.0	195.3	183.0	213.9	1806.3
1986	105.4	139.5	150.0	213.9	177.0	164.3	1688.8
1987	105.4	139.5	171.0	192.2	198.0	244.9	1870.7
1988	133.3	145.7	165.0	220.1	210.0	176.7	2067.1
1981-88	104.6	119.7	163.5	188.3	184.5	185.6	1792.8

3.2.5 Reservoir details

Mindu Dam is 1.56 km long and up to 12.5 m deep, retaining a reservoir approximately 3.50 km long and on average 1.50 km wide. The spillway is an overflow weir located upstream of the dam. The spillway has a design flood discharge capacity of 710 m^3s^{-1} at a flow depth of 2.2 m. In order to allow for existing water abstraction rights from the Ngerengere river downstream of the dam, the required compensation water discharge from the reservoir is 16000 m^3day^{-1} (Gibb, 1986).

Table 3.6 Stage-area-volume relationship for Mindu Dam

Stage (m)	Area (km^2)	Original volume (Mm^3)	20-year volume (Mm^3)
499.0	0.00	0.00	0.00
501.5	1.00	1.50	1.50
502.0	1.15	2.00	1.95
503.0	1.45	3.00	2.85
504.0	1.80	4.50	4.20
505.0	2.20	6.75	6.23
506.0	2.85	9.25	8.48
507.0	3.85	12.78	11.65
508.0	4.90	18.00	16.35
509.0	5.95	23.25	21.08
509.5	6.50	25.75	23.33
510.0	7.00	28.50	25.80

The variation in reservoir area and capacity with stage is tabulated in Table 3.6 derived from Gibb (1986). At the spillway crest level of 507 m (full supply level) the capacity is 12.72 Mm^3 comprising approximately 1.5 Mm^3 dead storage and 11.28 Mm^3 live storage. The proposed second stage raising would put the spillway crest at 509.50 m, increasing the live storage to an estimated 24.25 Mm^3. The stage-area and stage-volume curves provided by Gibb (1986) stopped at stage 507 m. Gibb (1976) provide some information on stage-area and stage-volume relationships for intermediate levels from 507 m to 509.50 m, but these data were inconsistent with those provided in the dam operation and maintenance manual (Gibb, 1986); for example, Gibb (1976) give the capacity at 507 m as 10 Mm^3, whilst Gibb (1986) give it as 12.72 Mm^3. Since the exact relationships were unclear, constant relationships were assumed and the Gibb (1986) curves were extrapolated to 510 m. Also shown in Table 3.6 is the allowance for sedimentation after 20 years (which will be reached in 2005). The rate of sedimentation specified in the MAJI Design Manual (1986) is a loss of 0.5% of the capacity per year. This has been taken off the live storage i.e. after 20 years the capacity will be only 90% of the original. Sedimentation is a considerable problem in the region, due to intense agriculture upstream, and the 0.5% loss estimate may well underestimate the true figure. It is recommended that studies of sediment transport and siltation rates are carried out in order to improve estimates of the rate of decline of the dam capacity.

Some spot readings of dam water levels between January 1987 and April 1993 were provided, but they were of little direct use since they did not provide a continuous record and they were not accompanied by any corresponding abstraction and release figures. They do however show the highest recorded water level of 508.50 m (above the spillway crest) to have been in April 1993, and the lowest recorded water level of 506.50 m (below the spillway crest) to have been in October 1988. During the 1993 flood, extensive damage was done to the gabions and mattresses lining the spillway discharge channel below the dam.

3.2.6 Rainfall-runoff modelling

An attempt was made to use the available flow series at the upstream stations of Konga and Mgera, or the downstream station of Kihonda, to generate the reservoir inflow series. However, without extension, these records are too short (25 years, 6 years and 10 years, respectively) to allow a good estimate of reliability of the reservoir yield to be made. In order to extend the records, the Pitman rainfall-runoff model (Pitman, 1973) was used in conjunction with the 64 years of catchment average rainfall data.

The Pitman monthly model is based on empirical equations representing surface runoff, soil moisture changes, groundwater infiltration and other processes. Each of these equations contains parameters which have to be evaluated or chosen. The model was originally developed for use in South Africa, but work by Pitman has generalised the model to arid, semi-arid and humid conditions, highlighting the important parameters in each case and enabling estimates of sensible initial values. The model has been applied to a broad range of catchment types and climate types throughout southern Africa, and has been found to perform satisfactorily in numerous water resources studies.

The inputs to the model are monthly rainfall and evaporation, and the output is simulated monthly flows. The calibration is done by comparing the observed and simulated mean annual flow (MAR), the mean of the logarithms of the annual flows (mean(logs)) and the standard deviation of these logarithms (sd(logs)) (since the annual totals of runoff generally follow a lognormal distribution). In addition, the seasonal distribution of the monthly flows are compared. Fitting by MAR alone gives too much weight to the accurate prediction of high flows. To give some weight to the prediction of low flows, the fit of mean(logs) should also be examined, whilst sd(logs) is a useful indicator of the variability of the annual flows. All three annual indicators and the comparison of the seasonal distributions were used to fit the model.

In order to make as much use of the available data as possible, two different approaches were initially considered. The first approach involved fitting the Pitman model to the Konga and Mgera catchments, and then scaling up the resultant flows to the Mindu Dam catchment on the basis of relative catchment areas and catchment rainfalls; these flows could then be compared with the corresponding flows at Kihonda for the period of overlap. The second approach entailed fitting the Pitman model to the Kihonda catchment, and then scaling down the resultant flows to the Mindu Dam catchment and to the subcatchments on the basis of relative catchment areas and catchment rainfalls; these flows could then be compared with the corresponding subcatchment flows for the period of overlap. Both approaches excluded the Mlali river catchment upstream of the swamp for the reasons discussed in section 3.2.2 i.e. that the catchment makes a disproportionately small, if any, contribution to the flow in the Ngerengere.

However, results from both approaches proved inconsistent: where the flows from the Konga and Mgera were scaled up, they were much greater than the observed flow at Kihonda, and where the flows at Kihonda were scaled down they were much smaller than the observed subcatchment flows, particularly at Konga. These results are caused by the extremely variable hydrological behaviour of the catchments. The Konga catchment exhibits an extreme rainfall gradient, varying from 700 mm in the valley bottom to 3000 mm on the watershed, and making runoff assessment difficult. The other mountainous catchments also have high rainfall, resulting in high runoff, whereas the remainder of the catchment is flatter with much lower rainfall, resulting in less runoff. It appears that whilst the Mlali is making a disproportionately small contribution to the flow in the Ngerengere, the Konga catchment is making a disproportionately large contribution. In addition, the very localised and random nature of rainstorms in the region means that extreme flood events in one part of the catchment will not necessarily correspond with flood events of similar extremity in other parts of the catchment.

It is interesting to note that in their review of the design flood hydrograph for Mindu Dam, Gibb (1980) attempted and failed to calibrate a US Soils Conservation Service catchment model to the Konga catchment using parameters believed to be typical for the catchment, and came up with disproportionately high flows from the catchment. They also found the recorded flows at Kihonda to be considerably less than those estimated at Mindu Dam by other methods, and proposed the discrepancy to be due to attenuation in the intermediary 11 km of river channel and to losses due to bank spillage and bed seepage.

A more realistic approach was to estimate the flows at Mindu Dam directly for the period of overlap of the flow records at Konga, Mgera and Kihonda i.e. 1954/55 to 1958/59. The flows at Mindu Dam were treated as the sum of 3 areas which appear to have different hydrological characteristics, as discussed above. The flows at Mindu Dam were taken as the sum of:

- Flow at Konga - representing the part of the catchment with the highest rainfall and highest runoff.

- Flow at Mgera - representing the other mountainous catchments with high rainfall and high runoff. The flow was scaled up by a factor of 3.82 to represent the contribution from the similar area (in terms of rainfall and response) above the 1100 mm isohyet, excluding the Konga catchment. The scaling factor was based on the product of the ratio of the area of the Mgera catchment to the unaccounted area above the 1100 mm isohyet, and the ratio of the average rainfall of the Mgera catchment to the average rainfall of the aforesaid area above the 1100 mm isohyet.

- The remainder of the catchment upstream of the dam i.e. the lower altitude, lower rainfall and lower runoff area, was taken as the flow at Kihonda minus the flow at Konga and minus the scaled flow at Mgera. The flow was scaled down by a factor of 0.36 to represent only the contribution from the area between the 1100 mm isohyet and Mindu Dam (excluding the area upstream of the swamp). The scaling factor was based on the product of the ratio of the area of the Kihonda catchment (excluding the area upstream of the swamp and the area above the 1100 mm isohyet) to the area of the Mindu Dam catchment (again excluding the area upstream of the swamp and the area above the 1100 mm isohyet), and the ratio of the average rainfalls for the aforesaid areas.

Figure 3.7 compares the estimated flows at the dam with the observed flows at Kihonda and the observed and scaled flows at Konga and Mgera. The 5 complete water years of estimated monthly flow data at Mindu Dam were used for calibration of the Pitman model. The parameter values for the best fits of the model obtained are given in Table 3.7 and described in Pitman (1973). Table 3.8 gives the comparison of the annual flows and Figure 3.8 compares the seasonal distribution of flows. It can be seen that the agreement for all 3 annual flow measures is excellent, as is the seasonal distribution.

A further indication of the fit of the model is given in Figure 3.9 which is a plot of simulated against observed annual runoff. The overall fit is fairly good, and it should be remembered that poor fits are as likely to be due to limitations in the input data as to be the result of inadequacies in the model.

Table 3.7 *Parameter values used in Pitman model for Mindu Dam*

Parameter	Unit	Value
POW	-	1.5
SL	mm	0.0
ST	mm	265.0
FT	mm month^{-1}	39.5
GW	mm month^{-1}	0.0
AI	%	0.0
ZMIN	mm month^{-1}	2000
ZMAX	mm month^{-1}	2000
PI	mm	1.5
TL	months	0.25
GL	months	0.0
R	-	0.5

Table 3.8 *Comparison of observed and simulated annual flow characteristics*

Measure	Observed flows (Mm^3)	Simulated flows (Mm^3)
MAR	55.310	55.270
mean (logs)	1.720	1.717
sd (logs)	0.173	0.172
MAR (extended series)	-	67.510

The 64 years of monthly catchment average rainfall data were then used with the Pitman model to produce a 64-year sequence of simulated flows at Mindu Dam. This extended flow sequence is given in Table 3.9. The mean of this extended series is increased to 67.51 Mm^3 compared with 55.27 Mm^3 for the 5-year calibration period. However, examination of the rainfall series shows the period between 1950 and 1959 to have been anomalously dry, with a mean annual rainfall of 914.5 mm compared to 1001.7 mm for the entire 64-year series. Because the longer records of observed flows at Konga and Kihonda were not used in the calibration, a final check was carried out. The simulated flows at Mindu Dam were compared with the observed flows at Konga and Kihonda, in each case for both the calibration period and the non-calibration periods for which there were additional observed data. Relationships between the simulated and observed flows were derived for both periods. The results are shown in Figures 3.10 and 3.11, and it can be seen that there is little difference between the fitted lines for the calibration and non-calibration periods, indicating that the relationship between the simulated and observed flows over the calibration period is consistent over the longer, non-calibration period, and that the calibration based on the very short period of record is adequate.

Table 3.9 Extended flow sequence at Mindu Dam (October 1925 - September 1988)

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
1925	0.51	0.58	0.57	3.70	4.48	3.35	2.59	2.82	2.98	2.88	2.40	1.74	28.61
1926	1.20	1.45	1.84	1.76	1.41	3.54	18.15	9.04	3.54	2.35	1.61	2.07	47.95
1927	2.19	1.60	1.44	2.32	2.16	2.77	18.61	9.16	3.51	2.46	1.65	1.12	48.99
1928	1.16	1.05	1.69	1.99	1.38	1.67	11.65	14.86	6.57	2.60	2.00	1.43	48.65
1929	1.48	1.70	1.55	1.46	1.27	1.76	3.11	3.60	2.96	2.22	1.76	1.41	24.26
1930	1.02	0.69	2.24	14.33	9.86	28.37	19.68	6.80	3.27	2.11	1.43	1.00	90.80
1931	0.74	0.51	0.36	0.55	1.84	6.03	28.44	28.41	9.31	2.68	1.78	1.34	81.99
1932	0.96	0.67	1.10	1.66	3.08	4.04	16.35	10.79	4.54	2.56	1.73	1.24	48.72
1933	0.85	0.49	4.10	16.48	7.75	2.72	3.01	3.34	2.49	1.62	1.16	0.87	44.90
1934	0.62	0.59	0.62	0.92	1.08	2.44	11.31	10.13	5.18	3.12	2.27	1.51	39.81
1935	0.85	0.52	0.95	1.00	1.47	12.74	8.91	22.87	10.44	3.42	2.34	1.76	67.29
1936	1.38	1.15	1.60	7.06	16.27	7.82	37.90	24.66	17.68	7.23	2.48	1.62	126.83
1937	1.10	1.91	2.23	1.95	1.40	14.86	35.16	25.76	7.93	2.54	1.73	1.19	97.77
1938	1.16	1.36	1.80	1.81	1.93	14.97	21.90	9.05	3.80	2.79	1.87	1.15	63.59
1939	1.50	1.66	1.34	0.77	0.69	14.17	17.93	26.67	10.55	3.14	2.03	1.29	81.94
1940	0.76	0.52	1.13	2.62	3.57	12.95	25.60	10.52	3.51	2.52	1.89	1.37	66.95
1941	0.95	0.56	0.62	1.28	1.69	2.91	12.68	7.11	3.32	2.27	1.61	1.43	36.42
1942	1.36	9.81	21.42	8.38	1.89	4.83	39.45	22.90	6.19	2.68	1.93	1.38	122.20
1943	0.81	1.15	1.81	1.98	5.53	4.01	20.68	12.65	4.73	2.75	2.09	1.49	59.67
1944	0.88	0.65	0.61	0.98	1.45	3.51	22.32	13.80	5.51	3.56	2.50	1.67	57.44
1945	1.40	10.56	6.33	16.37	17.88	24.75	26.29	11.74	4.47	2.59	1.75	1.21	125.34
1946	0.77	0.50	1.15	1.40	0.78	1.07	11.10	7.42	3.82	2.45	1.79	1.41	33.66
1947	1.37	1.19	0.96	17.54	8.53	7.27	41.45	52.99	16.62	3.30	2.40	1.73	155.33
1948	1.03	1.08	1.53	2.02	1.82	3.58	10.82	6.68	3.64	2.88	2.06	1.35	38.69
1949	1.31	1.38	2.14	2.92	2.45	1.73	2.70	16.25	7.92	2.78	1.93	1.22	44.72
1950	0.70	0.39	0.46	1.06	1.91	11.56	26.17	14.56	5.03	2.59	1.75	1.33	67.51
1951	1.19	1.02	0.78	1.03	2.72	3.79	11.30	9.38	4.83	2.94	2.04	1.28	42.32
1952	0.90	1.85	15.91	7.75	9.25	5.40	12.04	10.43	5.01	2.74	1.89	1.49	74.66
1953	1.43	1.19	0.79	0.67	0.51	0.73	9.92	15.34	6.68	2.63	2.01	1.50	43.38
1954	1.10	0.73	0.82	2.42	3.76	3.51	12.45	19.89	7.98	2.56	1.77	1.16	58.17
1955	1.09	0.90	0.87	0.78	2.27	3.20	10.54	17.87	7.94	3.16	2.11	1.43	52.18
1956	0.95	0.98	1.55	2.46	12.36	6.69	34.09	16.38	4.51	2.60	1.63	1.08	85.28
1957	0.71	0.59	0.64	1.26	2.12	3.30	18.10	15.85	5.98	2.47	1.68	1.67	54.37
1958	1.63	1.46	1.38	1.05	1.52	12.62	19.50	8.08	3.31	2.50	1.81	1.31	56.16
1959	0.82	0.59	1.11	1.89	2.22	2.52	4.35	4.42	3.41	2.40	2.32	2.19	28.25
1960	1.66	1.15	1.25	2.62	3.04	14.52	52.03	19.22	3.72	2.71	1.80	1.16	104.89
1961	0.95	0.68	0.32	0.22	4.42	3.89	8.63	5.96	4.05	8.06	4.99	2.40	44.59
1962	4.04	17.82	22.30	14.38	5.03	2.50	9.43	11.06	5.30	2.47	1.80	1.27	97.39
1963	0.73	0.52	0.52	1.56	2.88	9.01	45.79	17.83	4.07	3.22	2.19	1.31	89.64
1964	0.80	20.03	9.04	2.55	2.48	21.16	33.23	11.90	3.05	1.98	1.39	0.96	108.56
1965	1.01	0.90	0.79	1.44	2.04	2.52	21.65	10.91	3.85	2.32	1.46	1.22	50.12
1966	1.76	2.20	4.50	4.29	3.88	4.50	11.13	6.67	4.01	2.97	1.96	1.29	49.15
1967	1.02	1.31	1.45	0.95	0.60	0.60	22.52	26.36	9.08	3.33	3.68	5.07	75.96
1968	3.81	3.34	22.15	9.80	2.62	18.31	45.50	16.78	4.14	3.01	1.90	1.14	132.50
1969	0.65	0.82	1.30	1.57	1.91	4.20	21.98	10.13	3.19	2.23	1.94	1.49	51.41
1970	1.28	1.60	1.24	5.09	4.73	8.16	15.48	7.37	2.99	1.95	1.37	1.19	52.46
1971	1.09	0.74	1.27	2.56	2.59	4.04	41.51	18.87	4.93	3.27	2.12	1.27	84.26
1972	0.72	0.35	0.21	0.89	2.16	8.74	26.56	33.44	11.22	2.74	2.16	1.83	91.02
1973	2.67	3.91	6.36	23.29	10.17	2.83	53.34	22.40	4.45	2.85	1.96	1.47	135.68
1974	1.03	1.25	3.63	3.34	1.89	1.61	33.09	26.07	7.97	3.00	2.11	1.39	86.39
1975	0.84	0.44	0.25	0.70	1.20	2.47	21.27	17.39	6.44	2.90	1.84	1.22	56.98
1976	1.02	0.90	1.03	1.58	1.59	2.08	12.06	7.07	4.00	3.24	2.22	1.67	38.46
1977	1.20	0.65	0.67	2.02	10.43	10.66	15.06	8.70	4.12	2.58	1.83	1.38	59.30
1978	1.43	1.35	11.95	16.35	6.78	7.82	23.44	10.05	3.01	2.12	1.60	1.09	86.99
1979	0.66	5.21	31.95	12.88	3.34	13.32	25.86	18.47	7.06	3.43	2.13	1.29	125.61
1980	0.85	0.77	1.50	1.92	2.09	1.63	2.44	6.78	4.60	2.34	1.65	1.21	27.79
1981	0.90	1.32	2.73	2.95	2.26	7.14	24.83	19.44	6.82	3.13	2.41	1.56	75.49
1982	0.99	0.64	1.37	1.75	1.01	0.62	1.64	3.31	3.60	3.32	2.77	1.73	22.75
1983	1.94	2.54	16.21	7.75	2.37	2.00	3.13	4.32	3.76	2.83	2.19	1.42	50.47
1984	0.85	0.53	1.55	4.05	3.55	3.24	39.58	23.80	6.46	2.72	1.70	1.04	89.06
1985	0.70	1.26	1.79	1.49	2.49	3.64	21.11	16.52	5.86	2.51	1.80	1.22	60.40
1986	0.70	0.63	0.88	2.37	2.96	2.66	8.93	21.03	8.89	2.61	1.66	1.07	54.40
1987	0.84	2.29	3.81	6.15	4.07	2.36	2.88	13.30	6.80	2.39	1.56	1.06	47.51
1988	1.04	0.97	0.62	0.47	0.55	5.61	5.00	3.31	2.68	2.29	1.78	1.73	26.07
Mean	1.17	2.02	3.72	4.23	3.68	6.45	19.93	14.39	5.62	2.86	1.99	1.45	87.51

* Year refers to January e.g. 1925 means October 1924 to September 1925

3.2.7 Reservoir yield analysis

Estimates of the yield which can be supplied for various return periods of failure are required for the existing reservoir capacity, and for capacities up to the maximum proposed level (Gibb, 1986). The probabilities of failure adopted were 1, 2, 5, 10 and 20%, equating to return periods of failure of 100, 50, 20, 10 and 5 years respectively. For the purpose of this study, the probability of failure is defined as a percentage, on an annual basis, and is calculated using all years during which a failure occurred in one or more months. This basis is not ideal as it does not incorporate any measure of the duration of each failure which corresponds to the severity of the drought. However, it is the measure used in most storage-yield analyses, and no readily accepted alternative has been established.

A large number of reservoir yield design procedures are available. The current study will assess reservoir yield by the failure rate method. For this method, the starting month must be a wet month so that the dry season is not split, and the wettest month of April was used. A monthly reservoir water balance is carried out and the number of annual failures of any duration is noted. This is then expressed as a percentage of the total number of years to get the probability of failure.

The failure rate method was used with the 64 years of monthly inflow data, the 64 years of rainfall at the dam and the mean monthly evaporations. A range of demands from the original design yield of 58000 m^3day^{-1} upwards were examined, for both the original reservoir and for the smaller capacity reservoir following 20 years sedimentation at 507 m (the current full supply level), 508 m, 509 m and the maximum proposed 509.50 m. The results are plotted in Figures 3.12 to 3.15, which show yield after compensation release (of 16000 m^3day^{-1}) against probability of failure both with and without the effects of sedimentation. The yields for the return periods of interest have been abstracted and are listed in Tables 3.10 to 3.13. Figures 3.16 and 3.17 show the variation in yield with capacity for each of the selected return periods for the original and 20 years sedimentation states, respectively.

Table 3.10 Results of reservoir yield analysis for Mindu Dam level 507 m

Return period of failure (yr)	Daily yield (10^3m^3) Original capacity	Daily yield (10^3m^3) 20-year capacity
5	61	56
10	56	51
20	54	49
50	52	47
100	50	45

Table 3.11 Results of reservoir yield analysis for Mindu Dam level 508 m

Return period of failure (yr)	Daily yield (10^3m^3) Original capacity	Daily yield (10^3m^3) 20-year capacity
5	76	72
10	71	66
20	69	64
50	66	62
100	64	60

Table 3.12 Results of reservoir yield analysis for Mindu Dam level 509 m

Return period of failure (yr)	Daily yield (10^3m^3) Original capacity	Daily yield (10^3m^3) 20-year capacity
5	90	85
10	84	78
20	79	75
50	76	72
100	74	70

Table 3.13 Results of reservoir yield analysis for Mindu Dam level 509.50 m

Return period of failure (yr)	Daily yield (10^3m^3) Original capacity	Daily yield (10^3m^3) 20-year capacity
5	96	89
10	88	82
20	83	79
50	80	76
100	78	74

3.2.8 Conclusions

The final estimates of the yield of Mindu Dam near Morogoro are based on direct estimation and Pitman model extension of the flow series at Mindu Dam using the long-term rainfall series at Morogoro. The fit of the Pitman model was reasonably good, producing a long sequence of reservoir inflows. Yield estimates were obtained for various levels up to the maximum proposed. A rise of 2.5 m in the dam gives an increase in yield of more than 50% at the 20-year return period of failure. However, as noted in section 3.2.5, the reservoir stage-volume relationship above the present dam height is unclear, and another study should be considered after a detailed survey of the area has been carried out. Furthermore, Gibb (1986) and Makinson (1987) express some concern over the potential stability of the embankment foundation should second stage raising of the dam take place. These concerns arises from piezometer and relief well data on the performance of the embankment, and they recommend a thorough investigation to predict the performance of the foundation seepage control measures under the influence of a deeper reservoir. However, the most serious current threat to the yield of Mindu Dam is siltation.

3.3 RIVER YIELD ANALYSIS

3.3.1 Background

The original water supply source of Morogoro town, the Morogoro river, is now unable to satisfy current, never mind future, demand by run-of-river abstraction. Despite having an abstraction water right of 4550 m^3day^{-1} at the Mambogo intake, it is reported to be able to reliably supply only 2275 m^3day^{-1}, with even this subject to short duration failures (Gibb, 1976). Therefore, looking to the future, when it is believed the Mindu Dam will also fail to satisfy demand, plans are under discussion regarding the abstraction of water from the Wami and Mgeta rivers located, respectively, 50 km to the north and 40 km to the south-west of Morogoro (COWIConsult/Interconsult 198?). The aim of this study was to assess the yield of the Morogoro at Mambogo (the present intake location), and the potential yield of the Wami and Mgeta rivers, shown in Figure 3.18. Table 3.14 gives details of the nearest flow gauging stations and the available records.

Table 3.14 Details of flow gauging stations for river yield analysis

Gauge No.	Name	Area (km^2)	Period of record	No. of years
1HA8/8A	Morogoro at Morogoro	23.3	1954-1989	36
1HB2	Mgeta at Mgeta	101.0	1954-1989	36
1G1	Wami at Dakawa	28500.0	1953-1989	37

Although the latter two rivers have been mentioned as possible sources of extra supply for Morogoro, there are no detailed analyses of the expected reliable yield from these rivers. In the current study, low flow frequency analyses have been conducted in order to ascertain reliable run-of-river yields assuming very limited (no more than 10 days) storage, and neglecting downstream water right holders.

In order to ascertain the reliable yield of a river it is necessary to establish the recurrence interval of low flow conditions. On unregulated rivers, low flows occur during periods of little or no rainfall when river water originates from natural storage within the catchment. Low flow frequency analysis gives frequency curves, based on data that are independent and homogeneous, which show the proportion of years, or equivalently the average interval between years, in which the river falls below a given discharge. Such curves can be used to determine the probability of occurrence of a flow event of specified magnitude. For any period of D-days duration, the method of deriving a low flow frequency curve is summarised below:

- Determine the minimum consecutive D-day flow in each year

- Rank them from highest to lowest

- Assign a plotting position to each rank using the Weibull plotting position

- Plot the discharge against the plotting position

- Draw a smooth curve through the points

Low flow frequency curves were derived for each of the three rivers at locations at the gauging stations specified in Table 3.14. Since there are no known proposals to incorporate significant amounts of storage in the river supply schemes (in fact JBG (1973) positively discounted the idea for the Morogoro), low flow frequency curves were derived for just 1-day, 2-day, 5-day and 10-day durations. Thus, for example, the 1-day curve gives an indication of the reliability of flows that can occur on any given day, while the 10-day curve indicates the reliability of average flow over a 10-day period.

3.3.2 Flow data

The data requirements for river yield analysis are primarily long records of good quality daily mean flow data. In low flow analysis, it is essential to ensure the independence of low flow periods. In this region of Tanzania the highest river flows tend to occur in April, and so a water year from April 1 to March 31 was used.

For each river gauging station, the Ministry of Water, Energy and Minerals (MAJI) provided hardcopy daily flow data published in Hydrological Yearbooks. However, these records were not complete and ceased in 1979/80. In order to extend the records to more recent times, stage measurements and rating equations were requested. MAJI provided computerised daily and sub-daily stage data, together with current meter measurements. For the Morogoro and the Wami stations, MAJI also supplied their best estimate of the rating equations. The stage data provided at each station consisted of either 1, 2 or 3 values per day. These frequencies of measurement mean that calculated flows would be of limited accuracy during periods of rapidly changing stage, but since this investigation was concerned with periods of low flow when the stage can be expected to change only very slowly, these data were perfectly adequate.

Time constraints did not allow the hardcopy daily mean flow values to be computerised, and because the stage data were generally more complete and extended for a longer period of time, it was decided to compute all flows from the stage data. Using the available current meter measurements, a satisfactory rating equation was determined at each location. At none of the locations could significant shifts in the rating over time be identified from the discharge measurements provided. The ratings equations developed at each station are discussed in the appropriate section below.

Using the IH(1994) rating equations, computerised stage data (converted from feet to metres where necessary) were converted to daily flows and mean monthly discharges. For the years when published MAJI data were available, the computed mean monthly discharges were compared with those published. This provided a simple way of checking the rating equation used. All the stations have gaps in their records, and in order to have as complete a dataset as possible for the low flow analysis, some daily flows were infilled by interpolation. This was generally done when the published MAJI data was complete (though where the MAJI flows came from in the absence of stage data is unclear), indicated periods of recession or constant rise. All infilled data were flagged as 'estimated' data in the database. In the tables of mean monthly flow which are included as Appendix A, where the calculated figure includes any estimated daily flows the monthly flow is flagged with the letter 'e'. A maximum of 20 missing days after infilling were allowed in a year, before the year was removed from the low flow analysis.

3.3.3 Morogoro river yield at Mambogo

The headwaters of the Morogoro river are on the north-western slopes of the Uluguru Hills. The river flows north through the town of Morogoro before flowing into the Ngerengere river. The gauging station is located in the Morogoro residential township, just downstream of the Mambogo intake, which supplies water to the town. The control is a 4.6 m crest Cipolletti weir. The catchment is very small (23.3 km^2) and is mainly wooded, with steep mountainous slopes.

The rating equation provided by MAJI was:

$$Q = 11.384(h - 0.0)^{1.5357}$$

Very few current meter measurements have been made at this station: just 16 between 1960 and 1979. However, those made confirm the MAJI equation (Figure 3.19), and in the current study this rating was used and applied to the entire stage record commencing 26/03/54. It is noted in the 1960 Hydrological Yearbook that the weir is drowned at 'high' stage, but the level at which this occurs is not specified. Consequently, this rating will not be valid for all stages, but since this study was interested only in low flows and there have been no current meter measurements made at stage greater than 0.5 m, this was not investigated further.

At this station the MAJI Hydrological Yearbooks contained published flow data from April 1954 until November 1979. Figures 3.20a and 3.20b show that apart from a small number of values, the mean monthly flow computed using the rating above match the MAJI published flows reasonably well. It is unfortunate that the largest discrepancies between the IH(1994) flows and the MAJI published flows are during very low flow periods. In particular, the low flows in December 1960, January 1961 and November 1971 are significantly different. The 1960 Hydrological Yearbook places the minimum daily flow for the Morogoro at 0.05 m^3s^{-1} in January 1961; however, in both December 1960 and January 1961 measurements of zero stage were recorded at the station, and if the rating above is correct, these correspond to zero flow. In November 1971 measurements as low as 0.02 m were recorded at the station. Since the MAJI published flows are considerably greater than the flows determined using the rating equation, the validity of this equation at low flows was questioned. However, JBG (1973) quotes Little, a former Regional Engineer in Morogoro, as saying ".....the Morogoro river has been too low to be recorded in October 1958 and 1960.....". As can be seen in Figure 3.20, the published October 1958 flow compares well with the IH(1994) flow, as do the values on two other very low flow months, December 1974 and February 1975. This suggests that very low flows do occur on occasion. Following correspondence with MAJI, it was decided that the more conservative IH(1994) flows should be used in the low flow analysis (Mwakalinga, pers. comm.).

Table A.1 (Appendix A) gives a summary of the monthly flow data, computed using the rating equation above and Figure 3.21 shows the entire monthly flow record derived for this station using all the available stage data.

Figure 3.22 shows the mean monthly flow for three periods (1954-1965, 1966-1977 and 1978-1989) compared to the CV for each month determined from the entire record. These results suggest that there has not been a major change in the flow regime of the river over time. The highest values of CV are in the dry season months, reflecting the low natural storage in the catchment, and consequently large variability in flow. The average daily flow for this catchment is 0.77 m^3s^{-1}, which corresponds to an effective average annual rainfall across the whole catchment of 1036 mm.

Low flow frequency curves were derived for Morogoro gauging station for durations of 1, 2, 5 and 10 days. Smooth curves were fitted to the data by eye, and the results for selected return periods are also tabulated. However, for the Morogoro river, the yield is required at the existing Mambogo abstraction point, which has been operating since the 1930s and which is located just upstream of the gauging station. Therefore, the entire flow record at Morogoro comprises flows from the river minus the amount supplied to the town. Daily records of abstractions at Mambogo were not provided, but estimates of mean daily abstractions of 0.010 m^3s^{-1} in 1954/55 and 0.015 m^3s^{-1} in 1956/57 are presented in JBG (1973). A new water treatment works was built in 1975, and the town water supply has the right to abstract up to 4550 m^3day^{-1}. However, Gibb (1976) report that this water right cannot be guaranteed to greater than 97% reliability, and for this reason the abstraction has been limited to 2275 m^3day^{-1} (0.026 m^3s^{-1}). This abstraction is reported by Gibb (1976) as having almost full reliability based on mean monthly flows, but it is noted that it can fail for short duration periods. Since the yield needs to be assessed at Mambogo, it was necessary to make some allowance in the low flow frequency curve derived at the gauging station for water removed upstream at the intake. In order to incorporate the water removed for supply, the following assumptions were made:

- In water years 1954-1956 water was abstracted at 0.010 m^3s^{-1}
- In water years 1957-1974 water was abstracted at 0.015 m^3s^{-1}
- In water years 1975-1993 water was abstracted at 0.026m^3s^{-1}

Having determined the low flow frequency curves for the river at the gauging station, these flows were added to the ranked flows and the curves derived again. Only the 3 lowest flows at the gauging station (all zero flow) were not changed. These 3 flows were left unaltered because it is known that the abstraction does fail on occasion. By making no change to these 3 flows, the assumption made was that there was total failure at the Mambogo intake on these occasions (September 1978, January 1961, and October 1958) with no water being abstracted for the entire duration of the very low flow period (i.e. up to 10 days). Adding the different amounts to the low flows altered their ranked position, and so some plotting positions changed. Figures 3.23 and 3.24 show the plotted flows for 1-day and 10-day duration curves, both with and without the abstractions. Smooth curves were fitted to both sets of data, and the tabulated results in Table 3.15 were taken from a curve lying mid-way between the two curves. These results therefore indicate the yield at Mambogo, assuming that historically, during low flow periods, the amount of water taken from the abstraction point was reduced, but not stopped completely, except on the occasions of the 3 lowest flows.

Table 3.15 Morogoro at Morogoro : results of low flow frequency analysis

Low Flow Duration	Return Period (yrs) (reliability)									
(days)	2	(50%)	5	(80%)	10	(90%)	25	(96%)	50	(98%)
	m^3s^{-1}	m^3d^{-1} +	m^3s^{-1}	m^3d^{-1} +	m^3s^{-1}	m^3d^{-1} +	m^3s^{-1}	m^3d^{-1} +	m^3s^{-1}	m^3d^{-1} +
1	0.056	4.8	0.020	1.7	0.009	0.8	0	0	0	0
2	0.060	5.2	0.028	2.4	0.014	1.2	0	0	0	0
5	0.067	5.8	0.029	2.5	0.016	1.4	0	0	0	0
10	0.069	6.0	0.033	2.6	0.016	1.4	0	0	0	0

+ thousands of m^3

From the length of record available (25 years with sufficient data for analysis), the results indicate reliable yield during low flow periods of 1 to 10 days. It is clear from the results that the river drys up for durations of up to 10 days approximately once every 25 years. Consequently, there is no abstraction that can be assumed to be 96% reliable for periods of less than 10 days. At Mambogo, the low flow of 1-day duration with a 90% reliability (i.e. 1 failure in 10 years) is 778 m^3day^{-1}. The 10-day duration low flow with 80% reliability (i.e 1 failure in 5 years) is 2592 m^3day^{-1}, and that with 90% reliability is 1382 m^3day^{-1}. These results seem to reaffirm the findings of Gibb (1976) that while water abstraction of 2275 m^3day^{-1} is almost fully reliable based on mean monthly flows, it does fail for 'short' duration periods. Furthermore, these results indicate that no abstraction can be guaranteed to greater than about 90% reliability for short duration periods, and the existing rate of abstraction of 2275 m^3day^{-1} is likely to fail on average every 4 to 6 years for durations of between 1 and 10 days.

3.3.4 Mgeta river yield at Mgeta

The Mgeta originates on the southern slopes of the Uluguru Hills. The river flows south and then south-east before it joins the Ruvu river. The control at this station, located in the Uluguru Hills 40 km south-west of Morogoro, is a permanent rock bar across the river. The catchment is small (101 km^2) and mountainous, consisting mainly of woods and bushland.

MAJI did not provide a rating equation for this station. Figure 3.25 shows the current meter measurements provided. Clearly there is considerable spread in the measurements made, and those made between November 1977 and May 1979 stand out as being very different to those made either before or after. Since measurements made after May 1979 revert to a stage-discharge relationship similar to that for measurements made before November 1977, it may be that in the intervening period the stage was read incorrectly, perhaps because the stage board was replaced inaccurately after being washed away during a flood. However, there is no corresponding jump in the daily stage measurements made through this period, so the daily stage measurements may have been corrected. Without detailed knowledge of the station history, this discrepancy could not be explained, and so the current meter measurements made in this period were omitted from the analysis. Several other outlying measurements, made at different times, were also judged to be inaccurate, and were also omitted. All the measurements not used are circled in Figure 3.25. There is no evidence of a significant change in the rating over time, and the following equation was applied to the entire stage record, commencing 01/06/54 (Figure 3.26):

$$Q = 8.153(h+0.071)^{2.560} \qquad hmax = 0.92 \text{ m}$$
$$Q = 17.155(h-0.081)^{2.620}$$

At this station the MAJI Hydrological Yearbooks contained published flow data from November 1959 until December 1980. Figure 3.27a shows that, except for the period January 1971 until June 1976, the IH(1994) flows match the MAJI published flows reasonably well, particularly during low flow periods. Figure 3.27b compares the time series of mean monthly flows computed using the rating equation above and those published by MAJI in the Hydrological Yearbooks. This clearly shows the difference between the flows during the period January 1971 to June 1976, and it is during low flow periods that the greatest discrepancy occurs. When these flows were queried, MAJI stated that lower part of the MAJI rating used from 01/01/71 to 15/06/76 was incorrect, and suggested that the IH(1994) results should be used for analysis (Mwakalinga, pers. comm.).

Table A.2 (Appendix A) gives a summary of the monthly flow data, computed using the rating equation above, and Figure 3.28 shows the entire monthly flow record derived for this station using all the available stage data.

Figure 3.29 shows the mean monthly flow for three periods (1954-1965, 1966-1977 and 1978-1989) compared to the CV for each month determined from the entire record. These results suggest that there has not been a major change in the flow regime of the river over time. The average daily flow for this catchment is 2.81 m^3s^{-1}, which corresponds to an effective average annual rainfall across the whole catchment of 880 mm.

Low flow frequency curves were derived at the gauging station for durations of 1, 2, 5 and 10 days. Smooth curves were fitted to the data by eye, and the results for selected return periods are also tabulated. Earlier references do not specify possible locations for abstraction points, and so the results presented here are for the Mgeta at Mgeta. Figure 3.30 shows the 1-day and 10-day duration low flow frequency curves. The 2-day and 5-day duration curves would lie between these two, and for reasons of clarity are not shown. However, all the results for return periods of 2, 5, 10, 25 and 50 years are tabulated in Table 3.16.

From the length of record available (i.e. 28 years with sufficient data for analysis), the results indicate reliable yield for low flow periods for 1 to 10 days. The 1-day flow with a 90% reliability is 46000 m^3day^{-1}, and with a 98% reliability is 31000 m^3day^{-1}. Similarly, the 10-day flow with a 90% reliability is 50000 m^3day^{-1}, and with a 98% reliability is 35000 m^3day^{-1}. It should be remembered that abstractions must make allowance for water right holders downstream.

These results would be significantly different if the published MAJI flows for the questionable period January 1971 to June 1976 were used in place of those computed using the IH(1994) equation. Table 3.17 shows the results if the published MAJI flows were used. In this case, the 1-day flow with a 90% reliability is 21000 m^3day^{-1}, and with a 98% reliability is just 3000 m^3day^{-1}. Similarly, the 10-day flow with a 90% reliability is 26000 m^3day^{-1}, and with a 98% reliability is just 6000 m^3day^{-1}. The difference is caused by the fact that the MAJI published flows include very low flows in the period January 1971 to June 1976, which actually include the 3 lowest flows in the record.

Table 3.16 *Mgeta at Mgeta : results of low flow frequency analysis using IH(1994) flows*

Low Flow Duration (days)	2 m^3s^{-1}	(50%) m^3d^{-1}+	5 m^3s^{-1}	(80%) m^3d^{-1}+	10 m^3s^{-1}	(90%) m^3d^{-1}+	25 m^3s^{-1}	(96%) m^3d^{-1}+	50 m^3s^{-1}	(98%) m^3d^{-1}+
	Return Period (yrs) (reliability)									
1	0.86	74	0.62	54	0.53	46	0.41	35	0.36	31
2	0.88	76	0.62	54	0.53	46	0.41	35	0.36	31
5	0.88	76	0.62	54	0.54	47	0.41	35	0.36	31
10	0.94	81	0.66	57	0.58	50	0.46	40	0.40	35

+ thousands of m^3

Table 3.17 *Mgeta at Mgeta : results of low flow frequency analysis using MAJI flows*

Low Flow Duration (days)	2 m^3s^{-1}	(50%) m^3d^{-1}+	5 m^3s^{-1}	(80%) m^3d^{-1}+	10 m^3s^{-1}	(90%) m^3d^{-1}+	25 m^3s^{-1}	(96%) m^3d^{-1}+	50 m^3s^{-1}	(98%) m^3d^{-1}+
	Return Period (yrs) (reliability)									
1	0.70	60	0.41	35	0.24	21	0.09	8	0.04	3
2	0.70	60	0.42	36	0.25	22	0.10	8	0.04	3
5	0.71	61	0.44	38	0.29	25	0.14	12	0.05	4
10	0.73	63	0.45	39	0.30	26	0.15	13	0.06	5

+ thousands of m^3

3.3.5 Wami river yield at Dakawa

The Wami originates in the Kaguru mountains and flows north-east, reaching the sea just north of Bagamoyo. The Dakawa gauging station is located at the Morogoro/Korogwe road bridge, 48km north of Morogoro. The station commenced operation on 14/11/53, and MAJI provided stage data (with some gaps) from this date until 30/09/88. It is a complex catchment (28500 km^2) covering a wide range of altitude, topography, soil type, vegetation and precipitation. The main feature of interest upstream of the station is the considerable area of swamp on the Mkata, the main tributary of the Wami, which is believed to have a significant impact on the low flow regime at Dakawa.

The rating equation provided by MAJI was a two-part rating with the change point at 4.0 m:

$$Q = 6.3106(h - 0.00)^{1.5997} \qquad hmax = 4.0\ m$$
$$Q = 51.5772(h - 3.02)^{1.7641}$$

This rating was examined and found to be generally satisfactory, except for a discontinuity at the 4.0 m change point. In the current study the equation was accepted as provided, but in order to remove the discontinuity, the change point was increased to 4.12 m. The rating was applied to the entire stage record, commencing 14/11/53. The rating equation is well defined for stage less than 4.0 m, but is less well defined for stage greater than 4.0 m, when the flow goes out of bank (Figure 3.31). However, since it is the low flows that were of interest in this study, no attempt was made to try and improve the upper part of the rating equation.

The MAJI Hydrological Yearbooks contained published flow data from December 1953 until November 1954, and from October 1958 until December 1980. Figures 3.32a and 3.32b show that the computed flows match the MAJI published flows reasonably well, particularly during low flow periods. Table A.3 (Appendix A) shows a summary of the monthly flow data, computed using this rating equation and Figure 3.33 shows the entire monthly flow record derived for this station.

Figure 3.34 shows the mean monthly flow for three periods (1953-1964, 1965-1976 and 1977-1988) compared to the CV for each month determined from the entire record. These results suggest that there has not been a major change in the flow regime of the river over time. However, the flows are very low for such a large catchment (particularly during the dry season of July to October). It is likely that this is a consequence of the large marsh upstream of the gauging station, which must store substantial volumes of water and effectively regulate the downstream flow (much like a reservoir). It is also probable that significant amounts of water are lost from the wetland area through evaporation. For this reason, the average daily flow at Dakawa is just 26.6 m^3s^{-1} which corresponds to an effective annual rainfall across the whole catchment of only 29.4 mm.

Low flow frequency curves were derived for the gauging station for durations of 1, 2, 5 and 10 days. Smooth curves were fitted to the data by eye, and the results for selected return periods are also tabulated. Earlier references do not specify possible locations for abstraction points, and so the results presented here are for the Wami at Dakawa. Figure 3.35 shows the 1-day and 10-day duration low flow frequency curves. The 2-day and 5-day duration curves would lie between these two, and for reasons of clarity are not shown. However, all the results for return periods of 2, 5, 10, 25 and 50 years are tabulated in Table 3.18.

Table 3.18 Wami at Dakawa : results of low flow frequency analysis

Low Flow Duration	**Return Period (yrs) (reliability)**									
(days)	**2**	**(50%)**	**5**	**(80%)**	**10**	**(90%)**	**25**	**(96%)**	**50**	**(98%)**
	m^3s^{-1}	m^3d^{-1+}	m^3s^{-1}	m^3d^{-1+}	m^3s^{-1}	m^3d^{-1+}	m^3s^{-1}	m^3d^{-1+}	m^3s^{-1}	m^3d^{-1+}
1	3.75	324	1.70	147	1.30	112	1.00	86	0.80	69
2	3.80	328	1.80	156	1.40	121	1.05	91	0.90	78
5	3.90	337	1.90	164	1.45	125	1.15	99	1.00	86
10	4.00	346	1.90	164	1.60	138	1.20	104	1.10	95

+ thousands of m^3

From the length of record available (i.e. 25 years with sufficient data for analysis) the results indicate reliable yield for low flow periods for 1 to 10 days. The 1-day low flow with a 90% reliability (i.e. 1 failure in 10 yrs) is 112000 m^3day^{-1}, and with a 98% reliability (i.e. 1 failure in 50 years) is 69000 m^3day^{-1}. Similarly, the 10-day low flow with a 90% reliability is 138000 m^3day^{-1}, and with a 98% reliability is 95000 m^3day^{-1}. Again, it should be remembered that abstractions must make allowance for water right holders downstream.

3.4 SPRING SOURCES

3.4.1 Background

Natural springs, where available, generally provide a safe supply of water of good quality, even though the yield is restricted to the dry season flow as is the case with natural rivers. To meet demands, it is usual for a number of springs to be linked together as the yields of individual springs are generally only a fraction of the total demand. The water supply at Morogoro is currently supplemented by 3 spring source intakes: 2 longstanding ones, at Kibwe and Kigurunyembe, and a recently developed one at Vituli. The current study was asked to attempt to assess the potential yield of the springs, given negligible data. Figure 3.36 shows the locations of the intakes in relation to Morogoro.

The groundwater potential of Tanzania is variable. Areas underlain by rocks of the PreCambrian basement complex rely on secondary features such as joints, fissures and weathering, whereas the younger sedimentary deposits, although also containing secondary features in places, generally yield water through primary porosity and permeability. According to the 1:5M Hydrogeological Map of Tanzania, Morogoro lies near a fault separating PreCambrian basement complex gneisses and metasediments to the south and east (i.e. the Uluguru Mountains), from more recent sedimentary deposits, composed mainly of sands, silts and clays, to the north and west. In fact, the town lies almost on top of a 3-way junction between an unproductive formation, a low-yielding formation, and a potentially fairly productive formation (up to 4 ls^{-1}). Evidence for a high permanent groundwater table is provided by the low-lying swamp on the Mlali catchment, and the groundwater potential of the region looks promising.

The spring source intake sites and surrounding areas were visited during the fieldtrip to Morogoro. The sites had many features in common: small, rapidly moving streams flowing from steep, intensively cultivated catchments into artificially-reinforced 'plunge pools', with overflow weirs to enable the water to carry on flowing downstream, and intake and washout pipes for the supply. The intake pipes lead downhill to storage tanks, and from there down to the town. Sedimentation and associated reduction of storage capacity in the pools are particular problems during the wet season when the washout pipes may have to be used several times a week. The visual evidence appeared to suggest that although the streams may indeed be spring-source dominated, the surface catchment might well make an important contribution at certain times of the year. Table 3.19 shows the estimated surface areas and catchment average rainfalls for the 3 spring sources at the intakes.

Table 3.19 *Estimated surface areas and catchment rainfalls for spring sources*

Site	Surface area (km^2)	Catchment rainfall (mm)
Kibwe	0.64	925
Kigurunyembe	3.33	980
Vituli	3.35	1446

Attempts to derive a relationship between the mean annual runoff and the catchment rainfall for Mgera, Morogoro, Konga and Mlali, and use this to estimate the mean annual runoff for the spring sources, proved inconclusive. COWIConsult/Interconsult (198?) report that Kibwe and Kigurunyembe can yield about 1000 $m^3 day^{-1}$ between them but Vituli, being recently developed, is of unknown yield. The estimate for Kibwe and Kigurunyembe may well be reasonable, but the data on which it was based is unclear (perhaps actual abstraction records?). With no meaningful data it is not possible to either confirm or improve on this estimate. A comprehensive study of the potential yield of the 3 spring sources awaits the implementation of a regular gauging program.

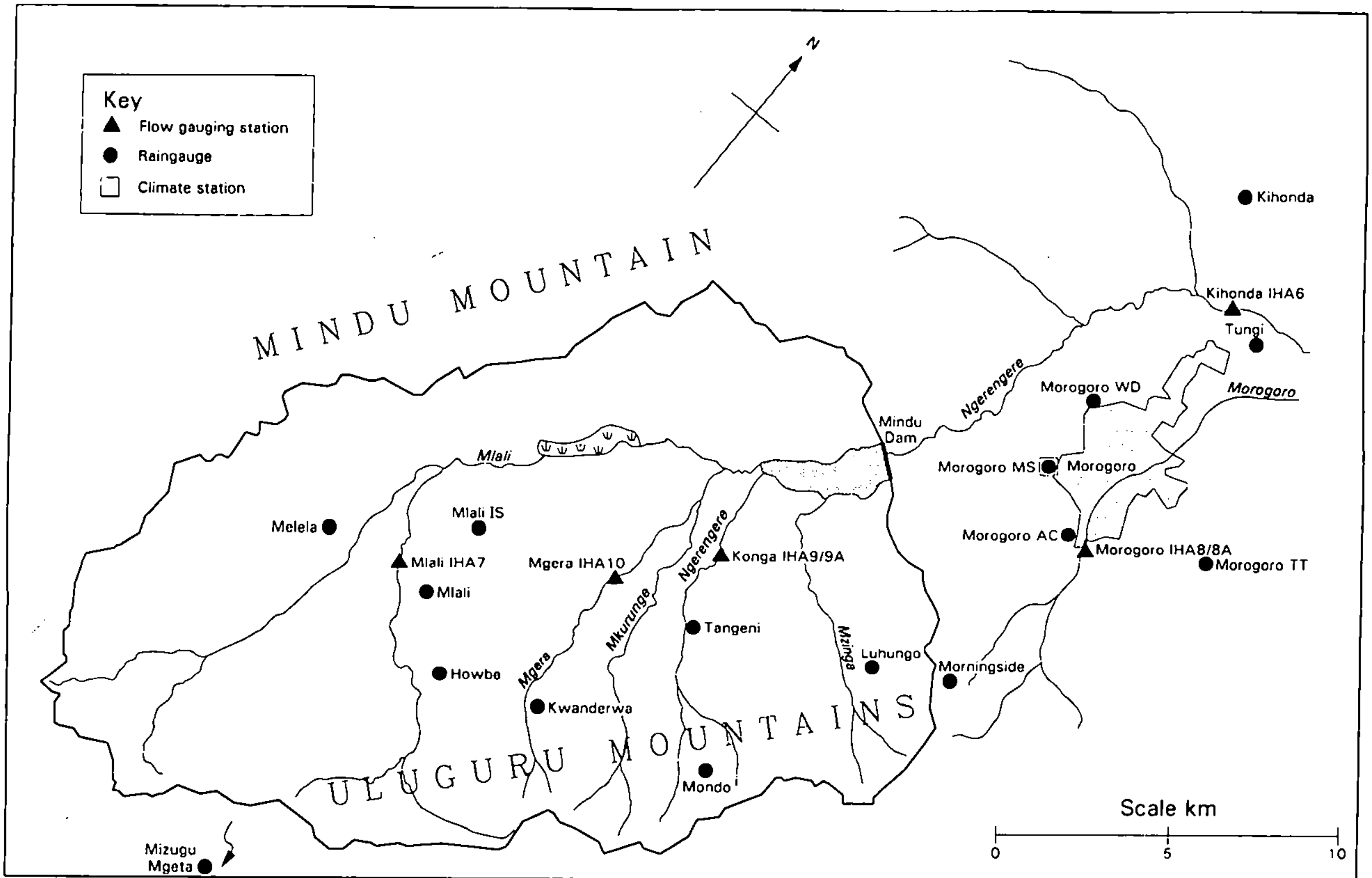

Figure 3.1 Plan of Mindu Dam catchment showing locations of gauges

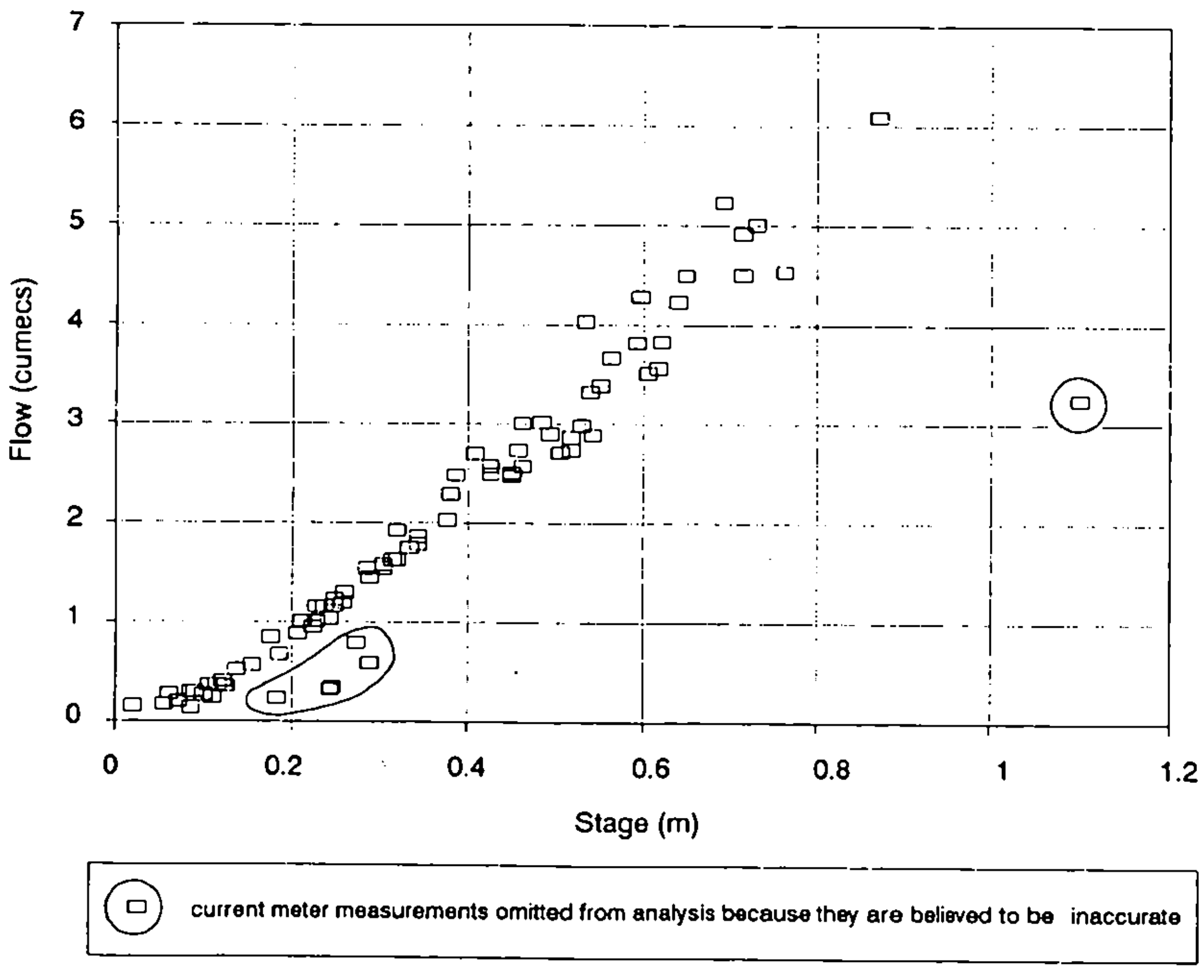

Figure 3.2 Current meter measurements for Ngerengere at Konga

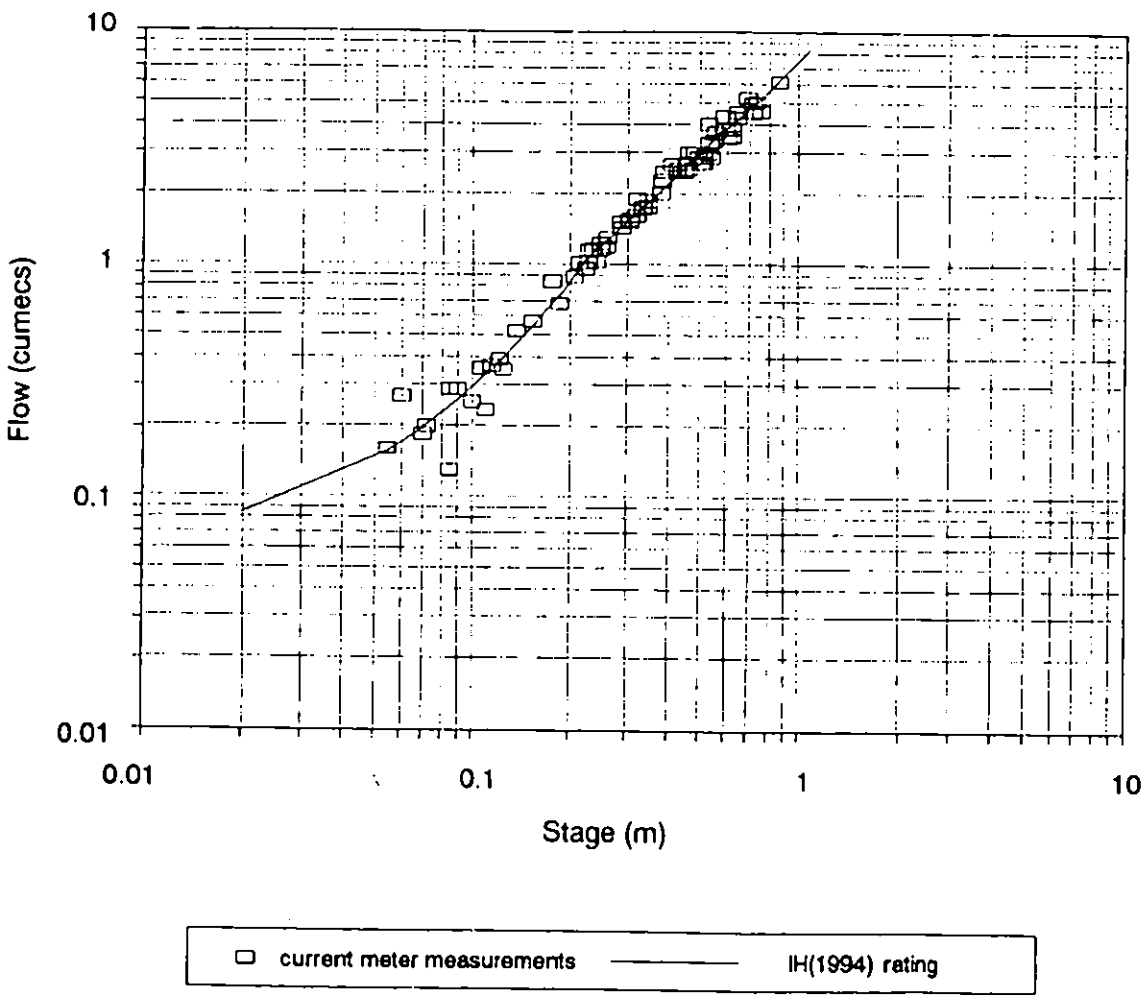

Figure 3.3 *Rating equation for Ngerengere at Konga*

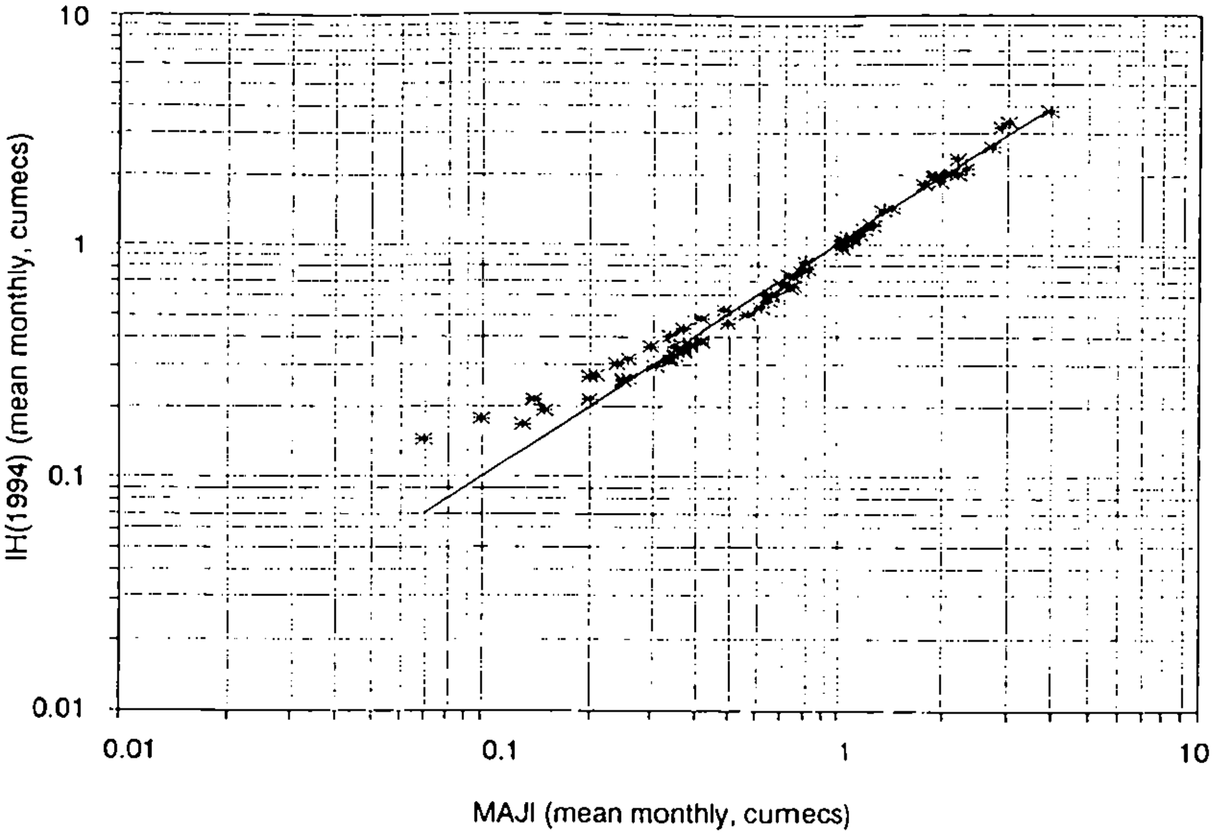

Figure 3.4a *Comparison of IH (1994) and published MAJI flows for Ngerengere at Konga*

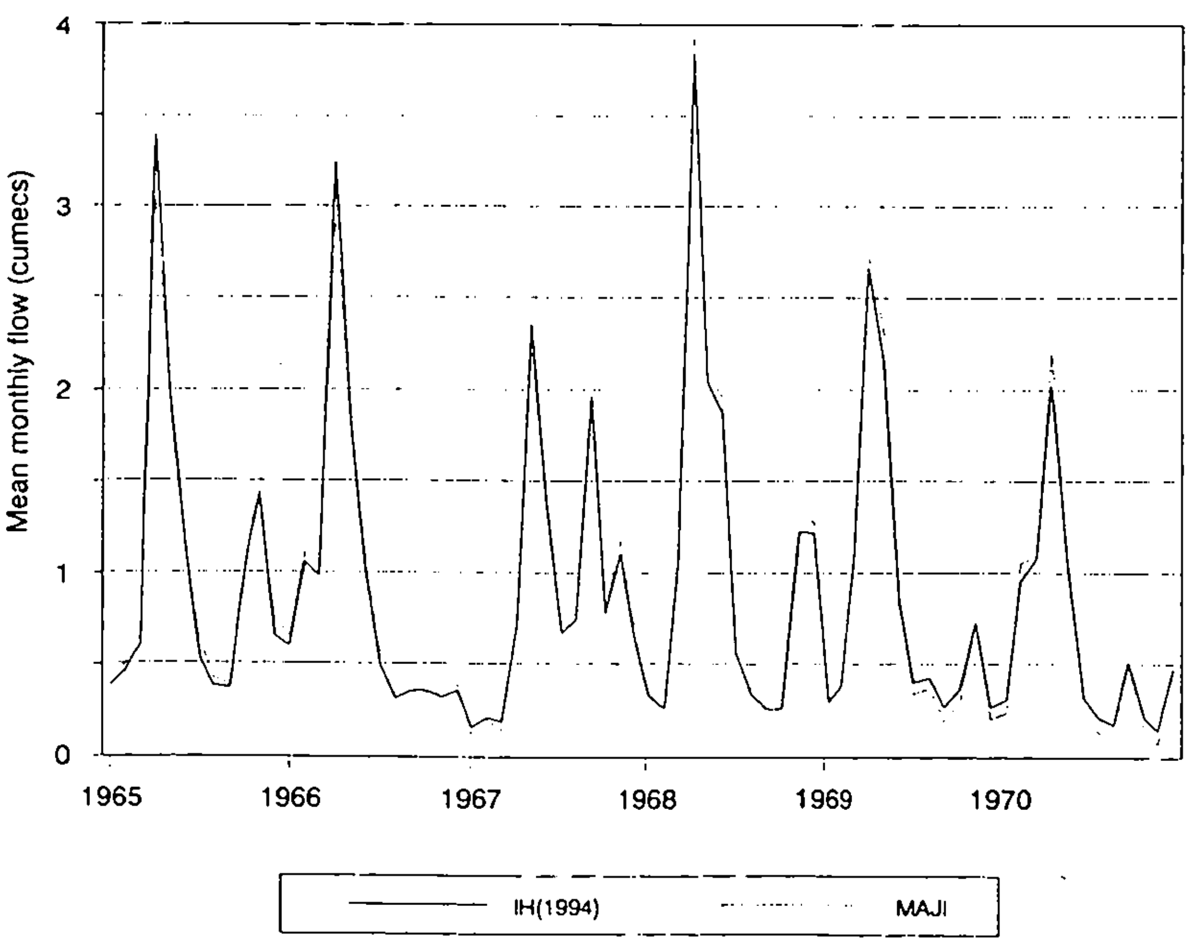

Figure 3.4b *Comparison of IH (1994) and published MAJI flows for Ngerengere at Konga*

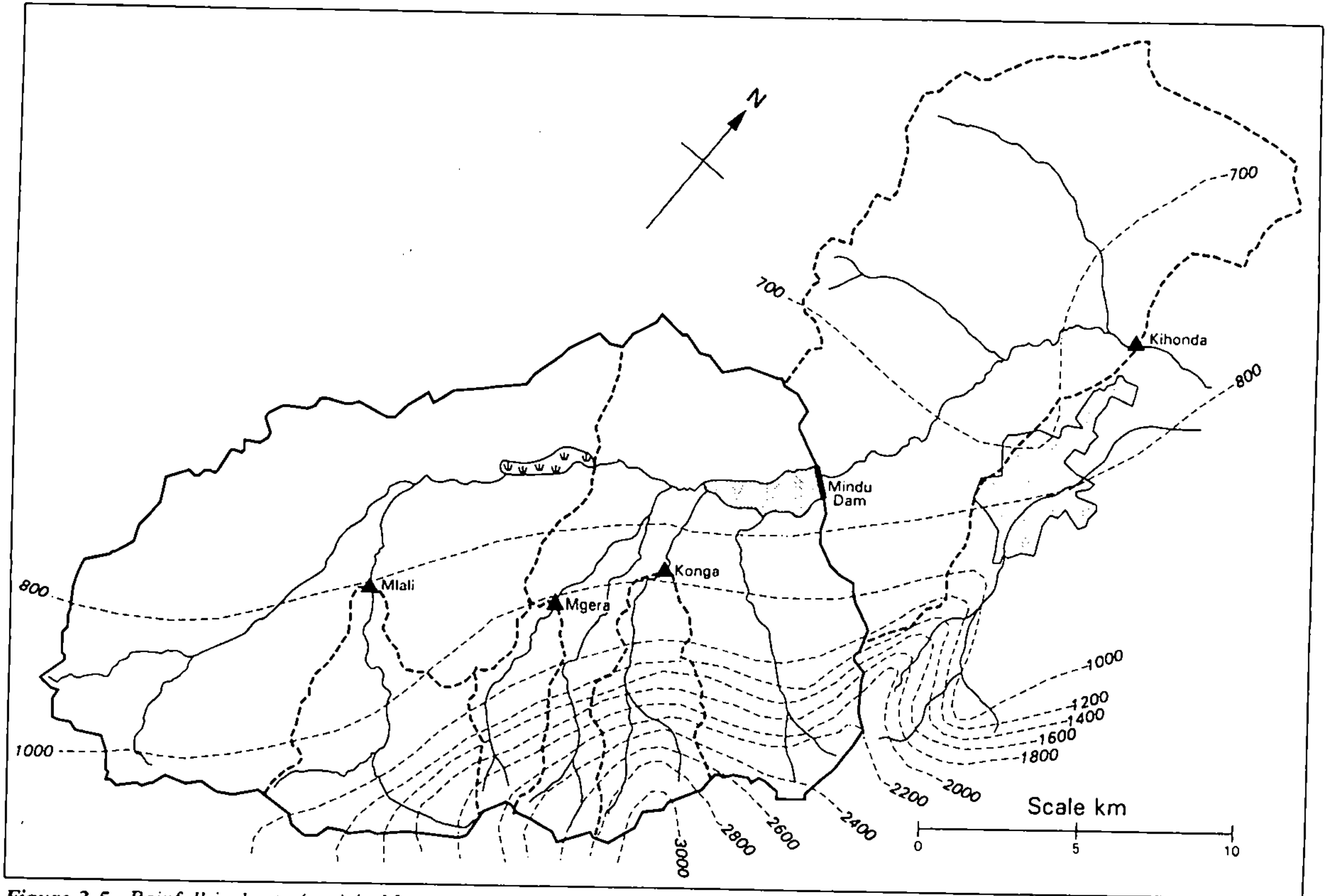

Figure 3.5 Rainfall isohyets (mm) in Morogoro region

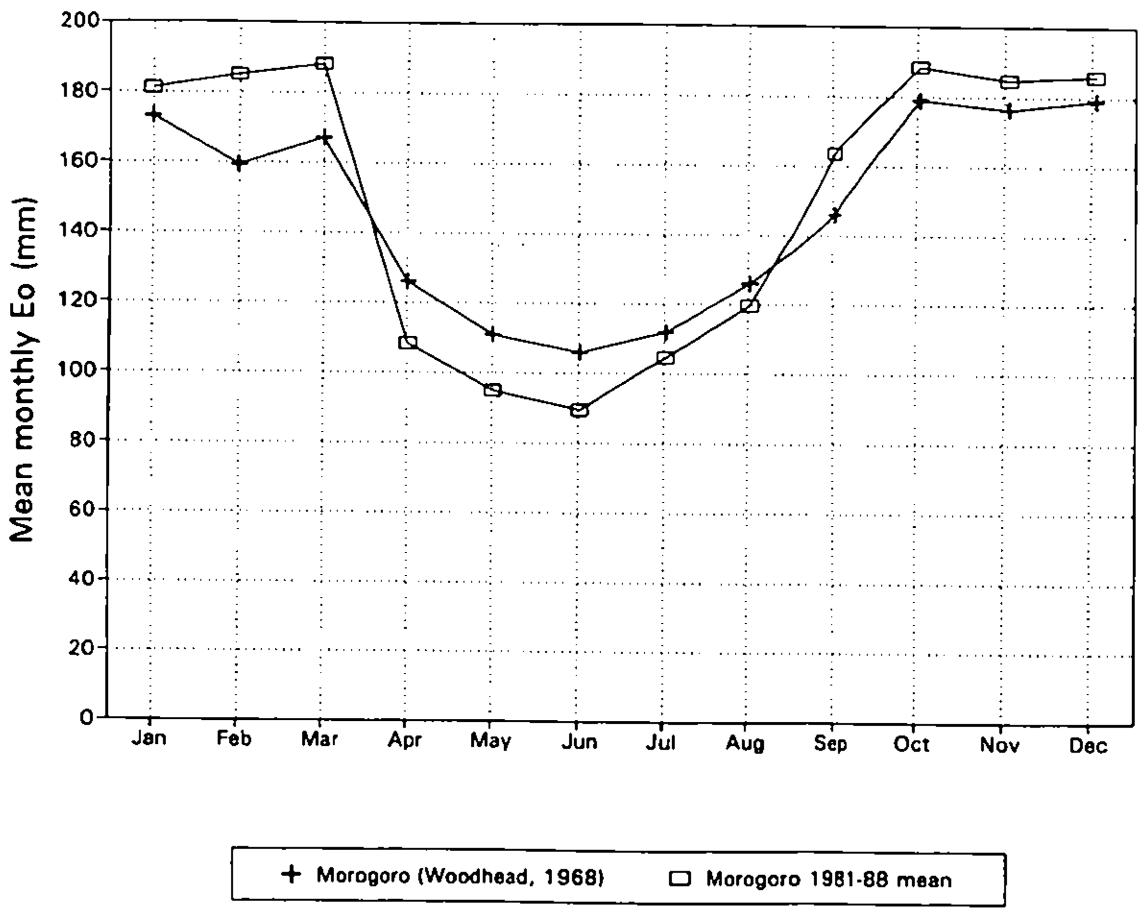

Figure 3.6 Monthly variation in open water evaporation

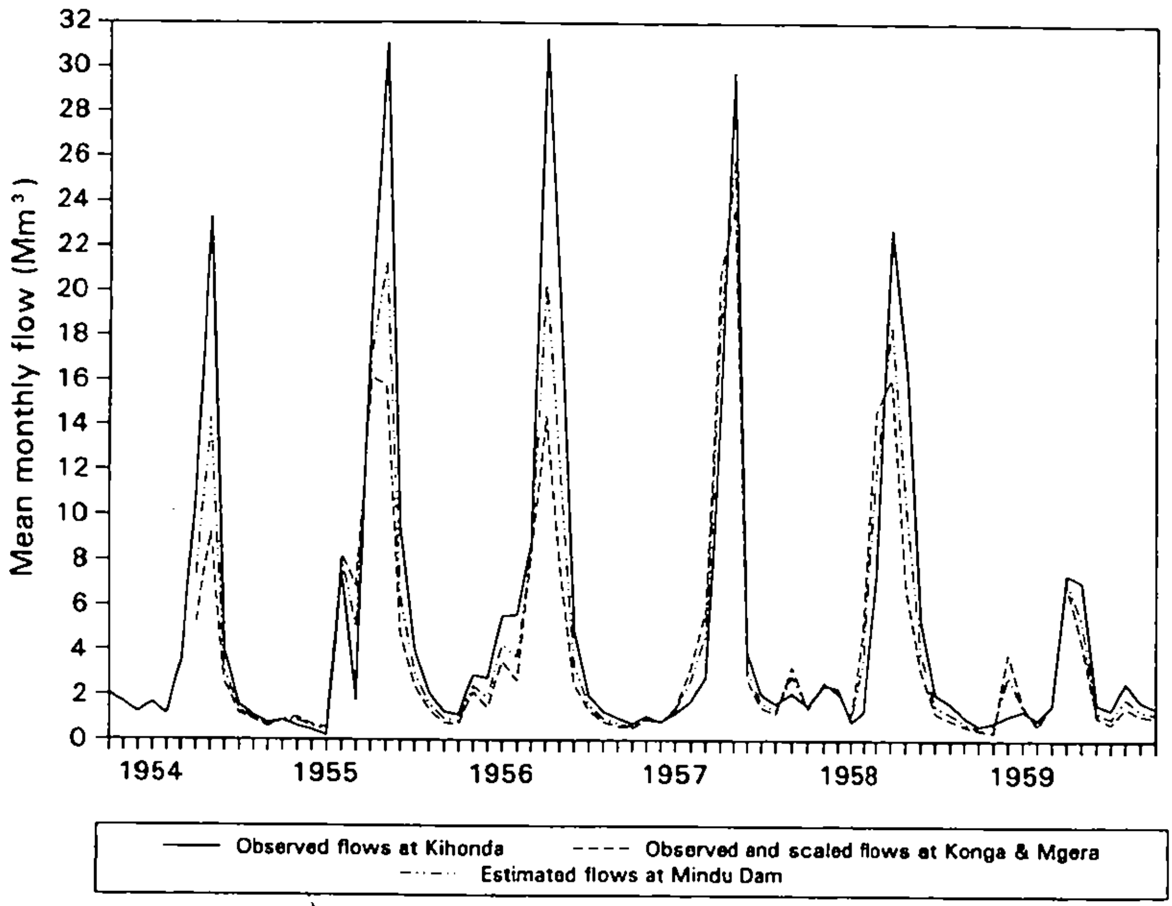

Figure 3.7 Comparison of estimated flows at Mindu Dam with 'parent' observed flows

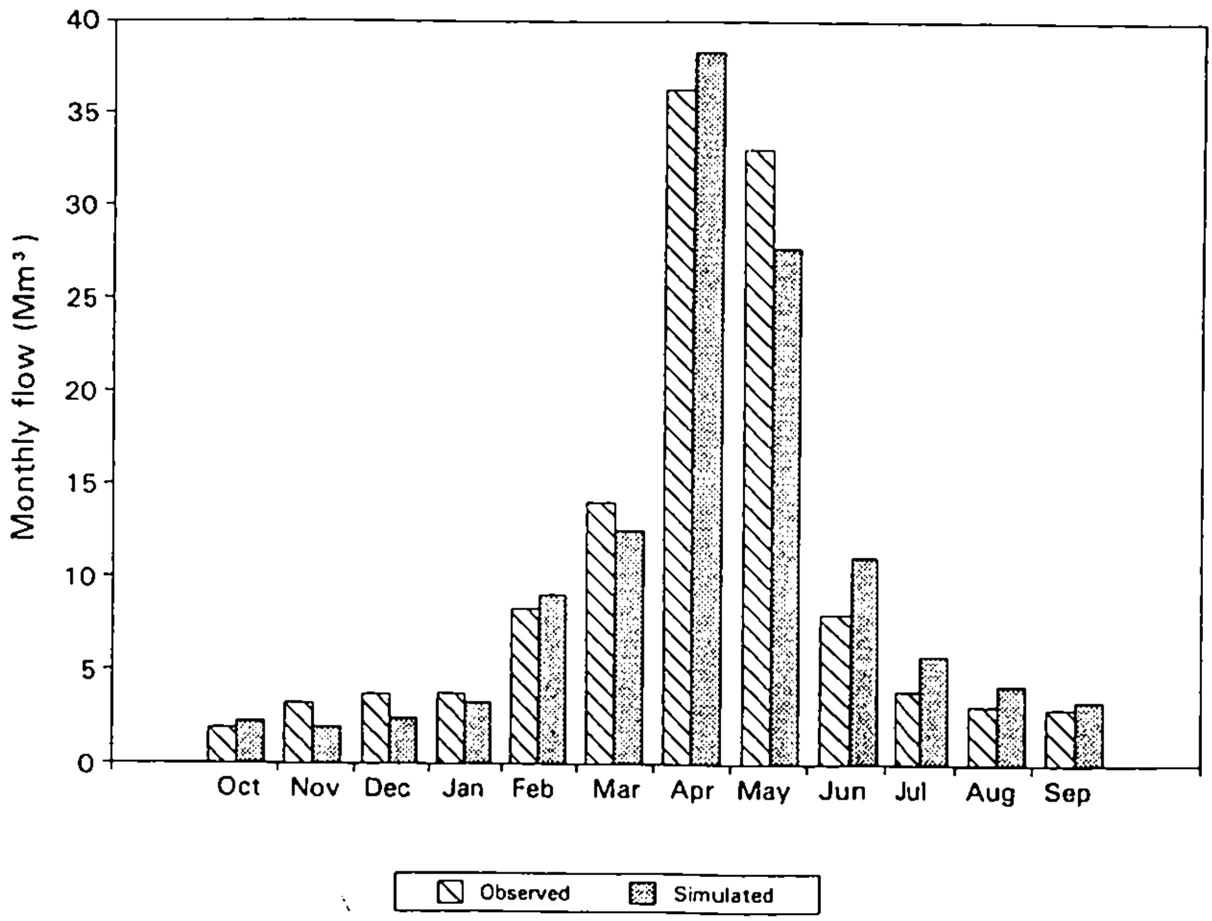

Figure 3.8 Comparison of seasonal distribution of observed and simulated flows from Pitman model calibration for Mindu Dam

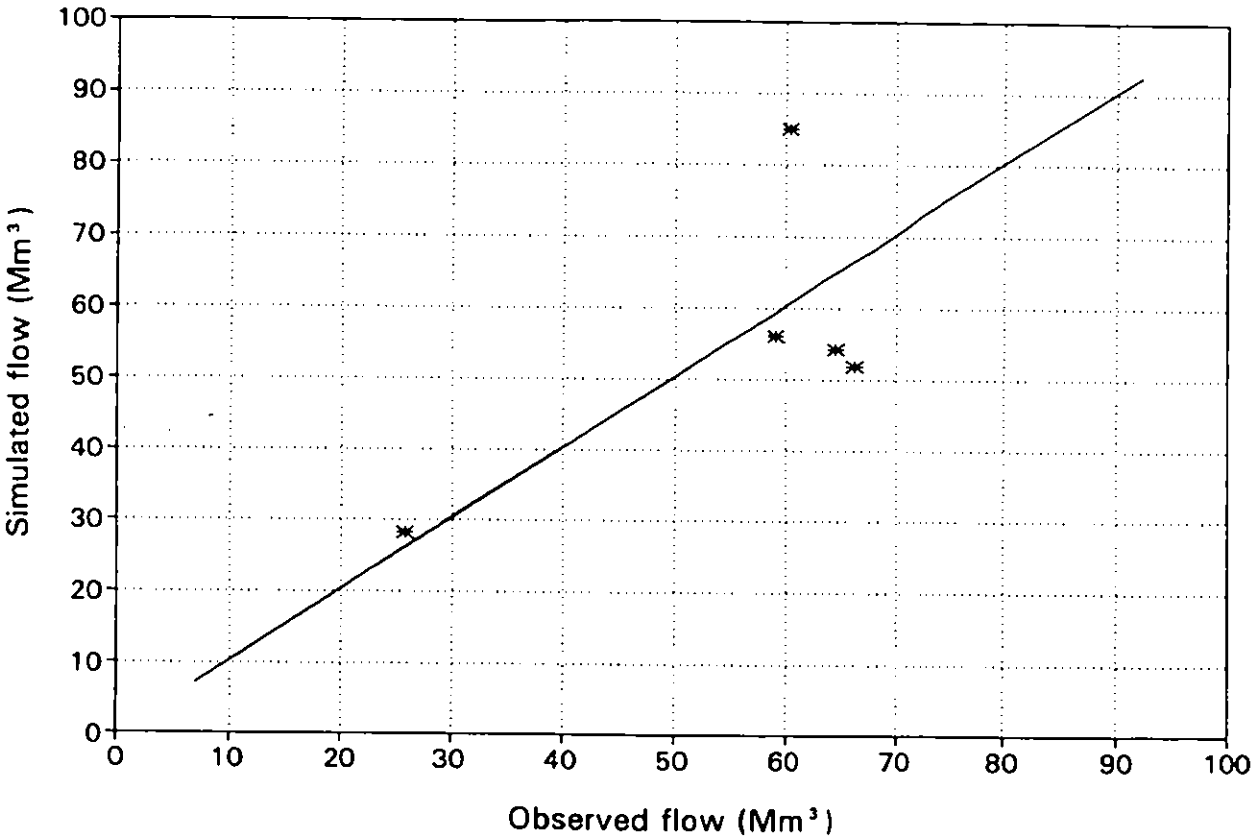

Figure 3.9 Observed and simulated annual flows from Pitman model calibration for Mindu Dam

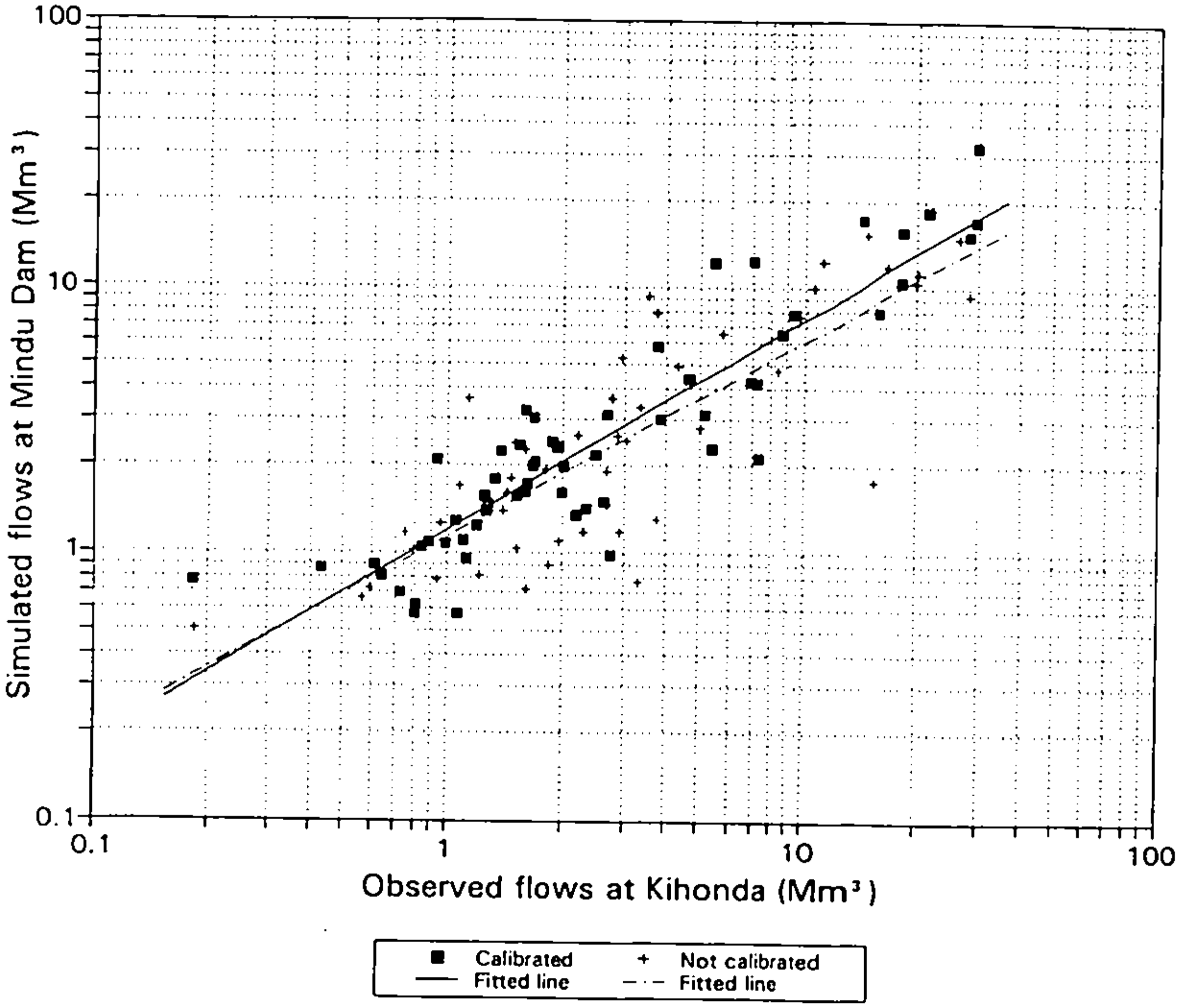

Figure 3.10 Relationship between simulated flows at Mindu Dam and observed flows on Ngerengere at Kihonda

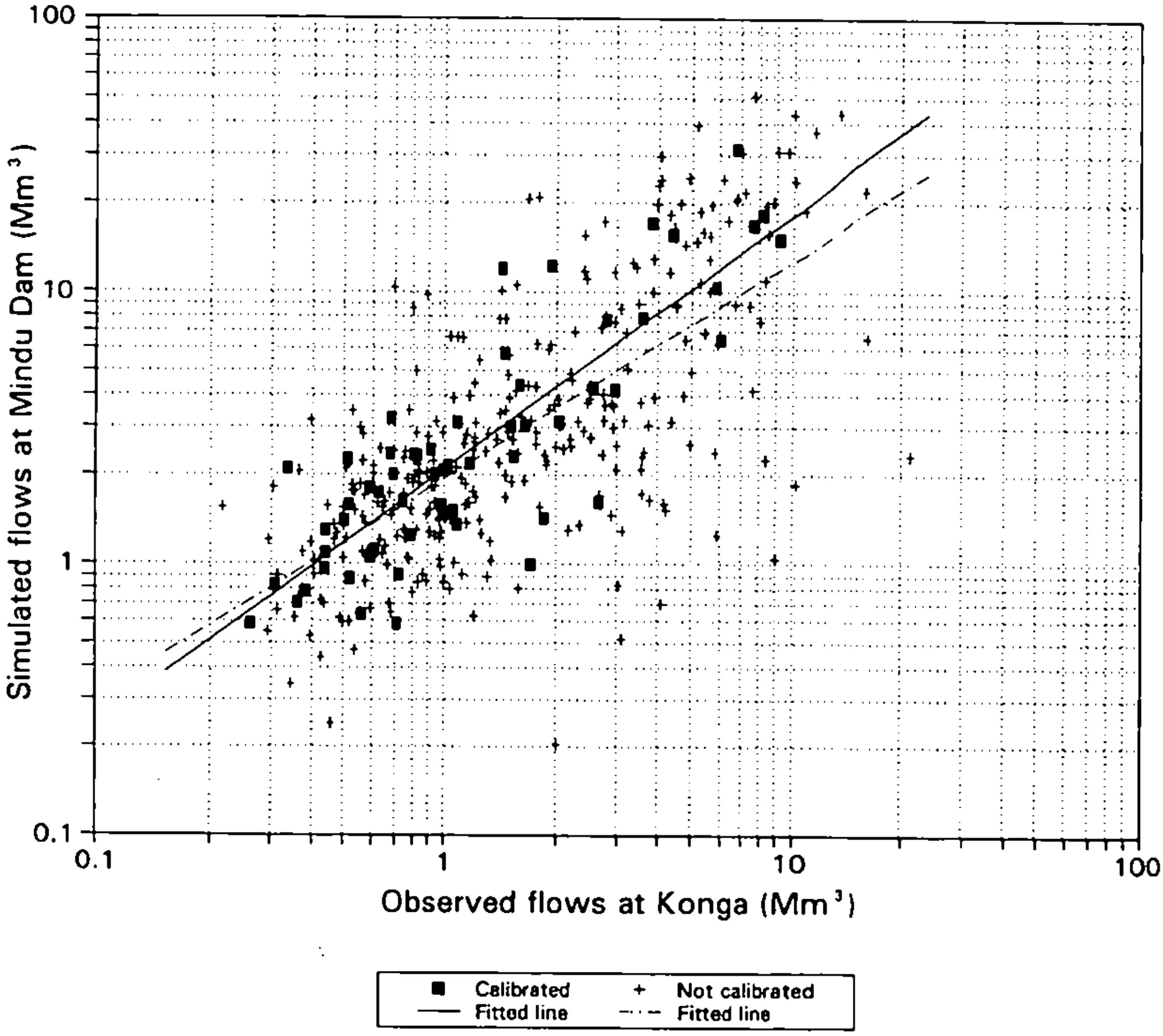

Figure 3.11 Relationship between simulated flows at Mindu Dam and observed flows on Ngerengere at Konga

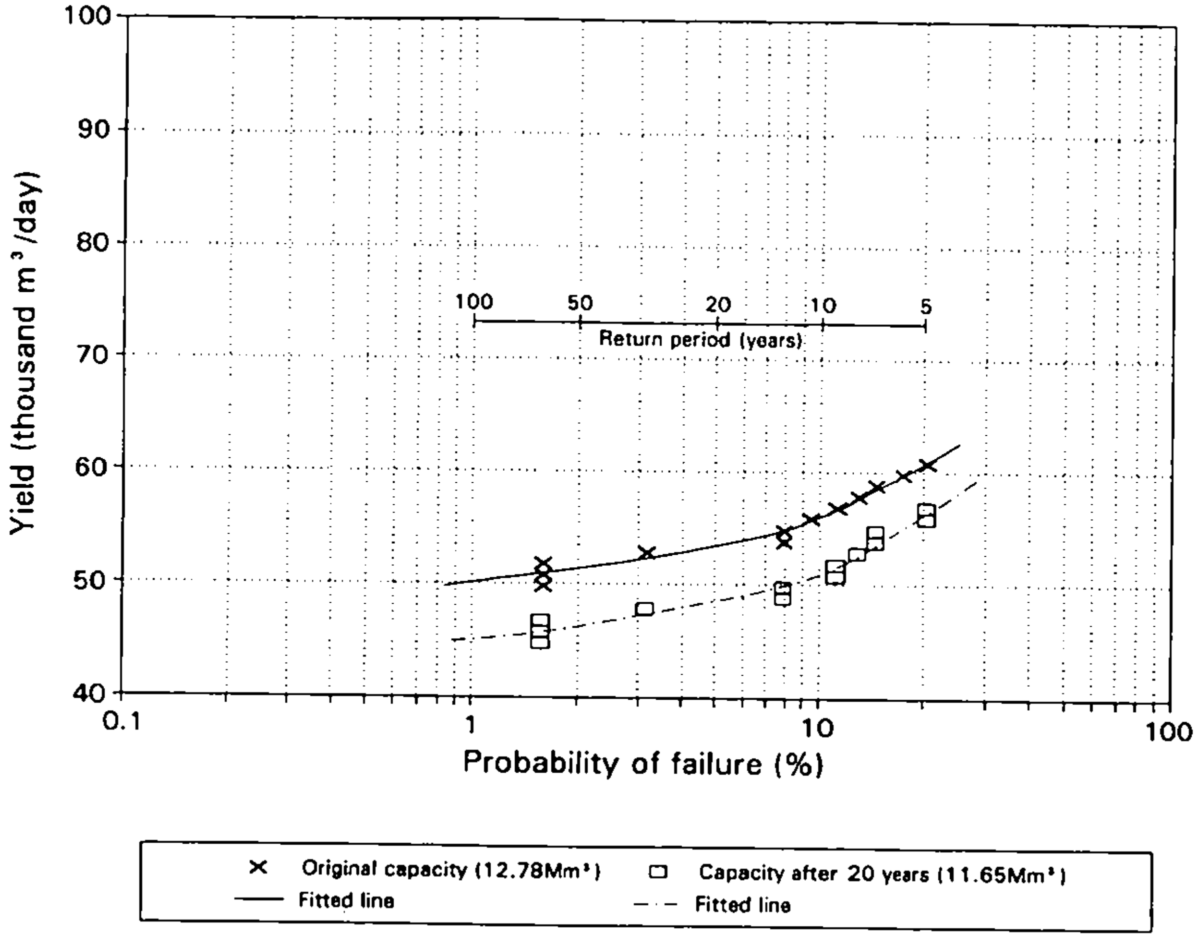

Figure 3.12 Results of reservoir yield analysis for Mindu Dam level 507.0m after compensation flow release of 16000m³/day

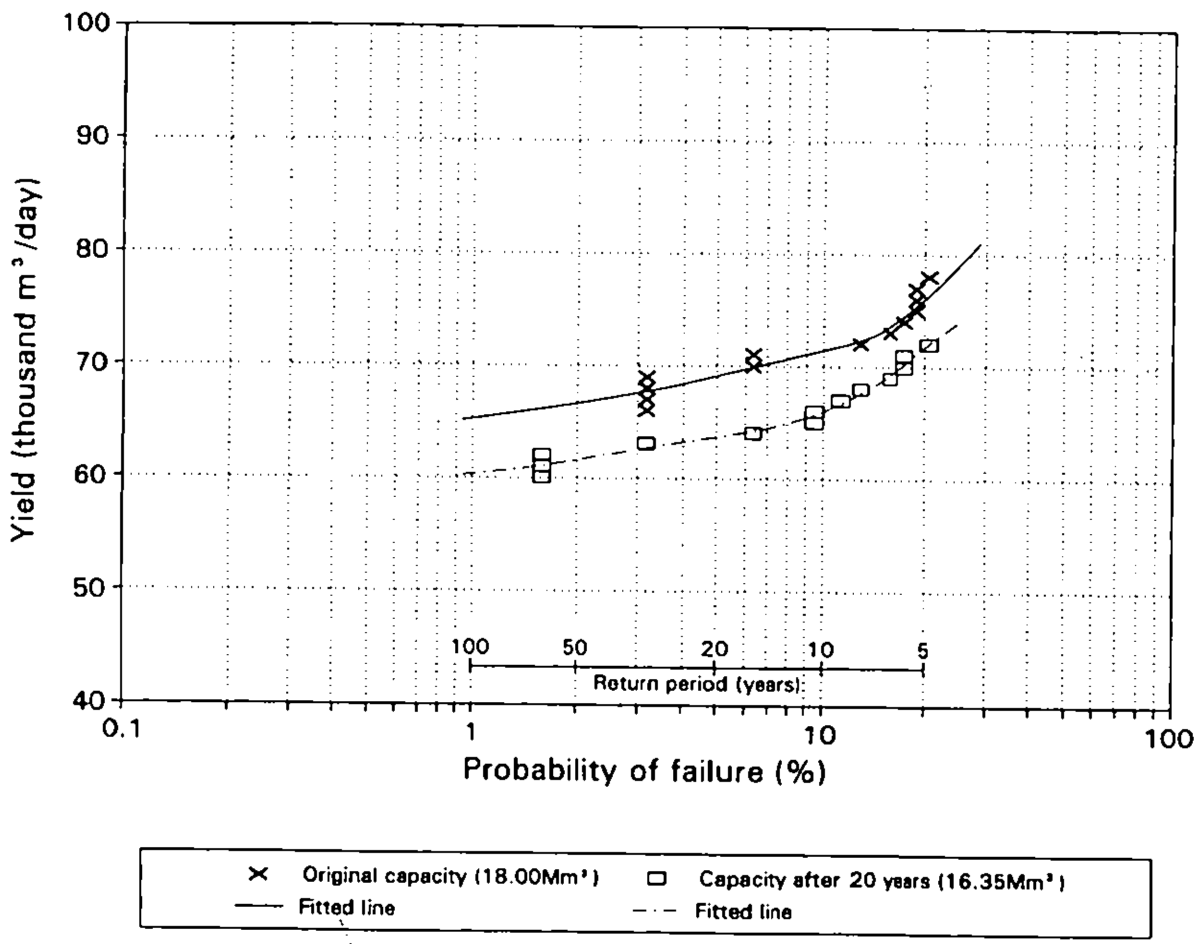

Figure 3.13 Results of reservoir yield analysis for Mindu Dam level 508.0m after compensation flow release of 16000m³/day

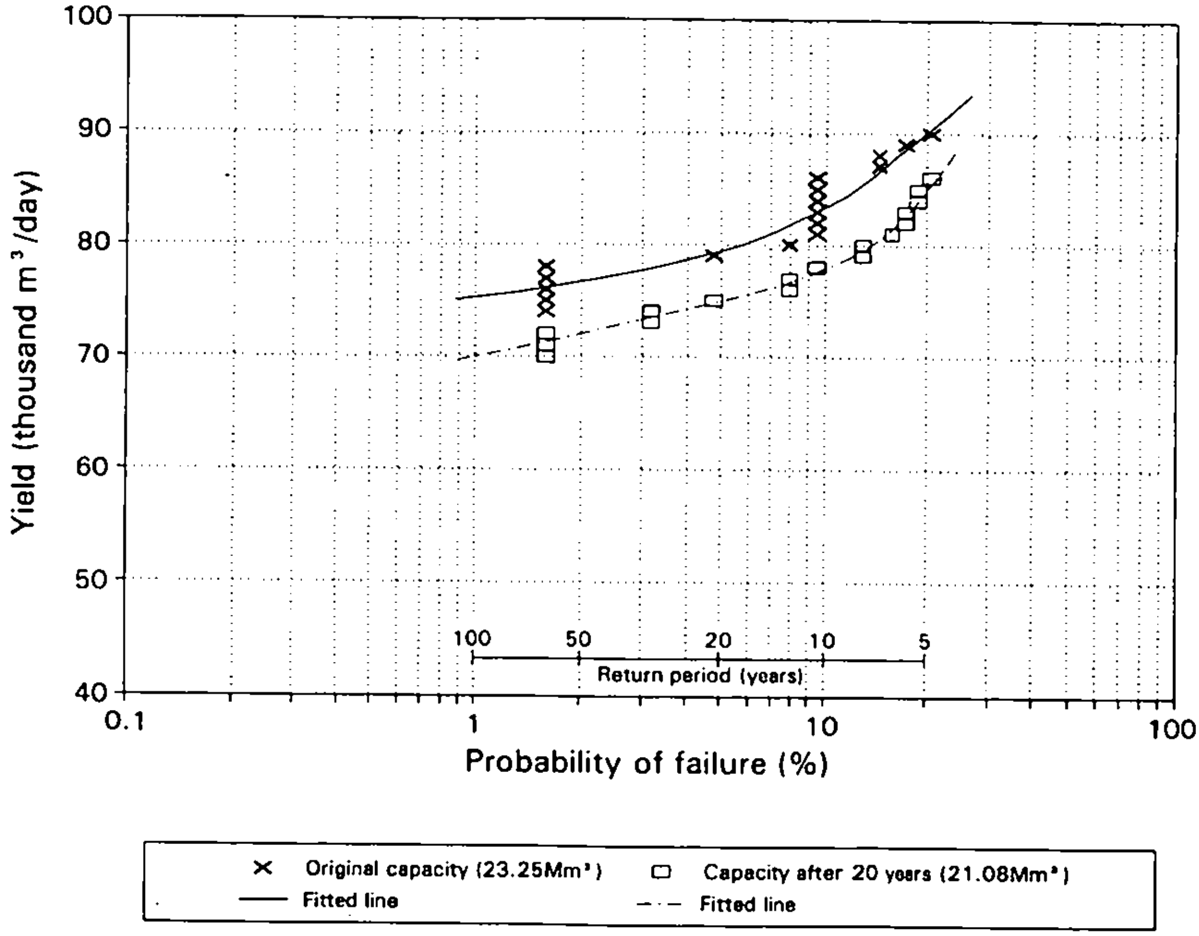

Figure 3.14 *Results of reservoir yield analysis for Mindu Dam level 509.0m after compensation flow release of 16000m³/day*

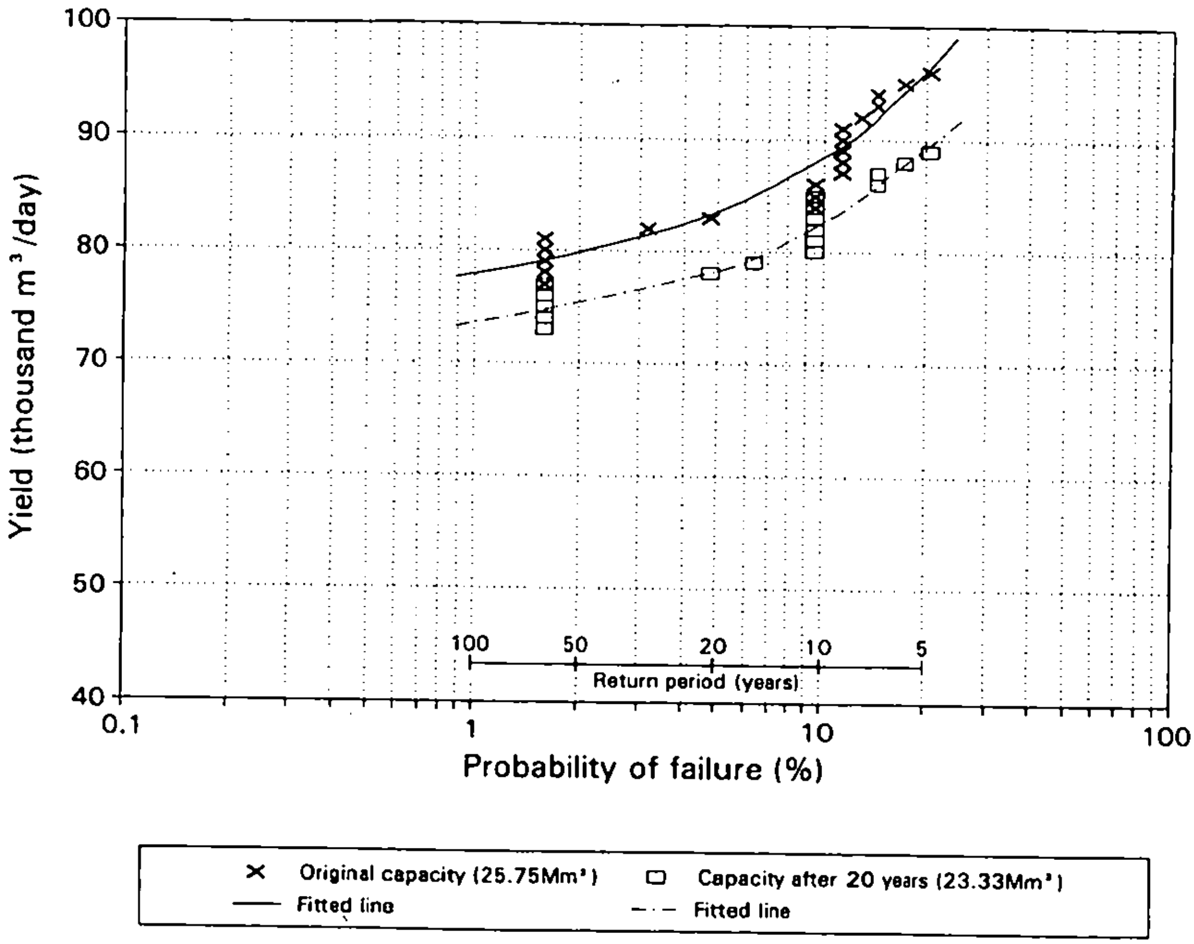

Figure 3.15 Results of reservoir yield analysis for Mindu Dam level 509.5m after compensation flow release of 16000m³/day

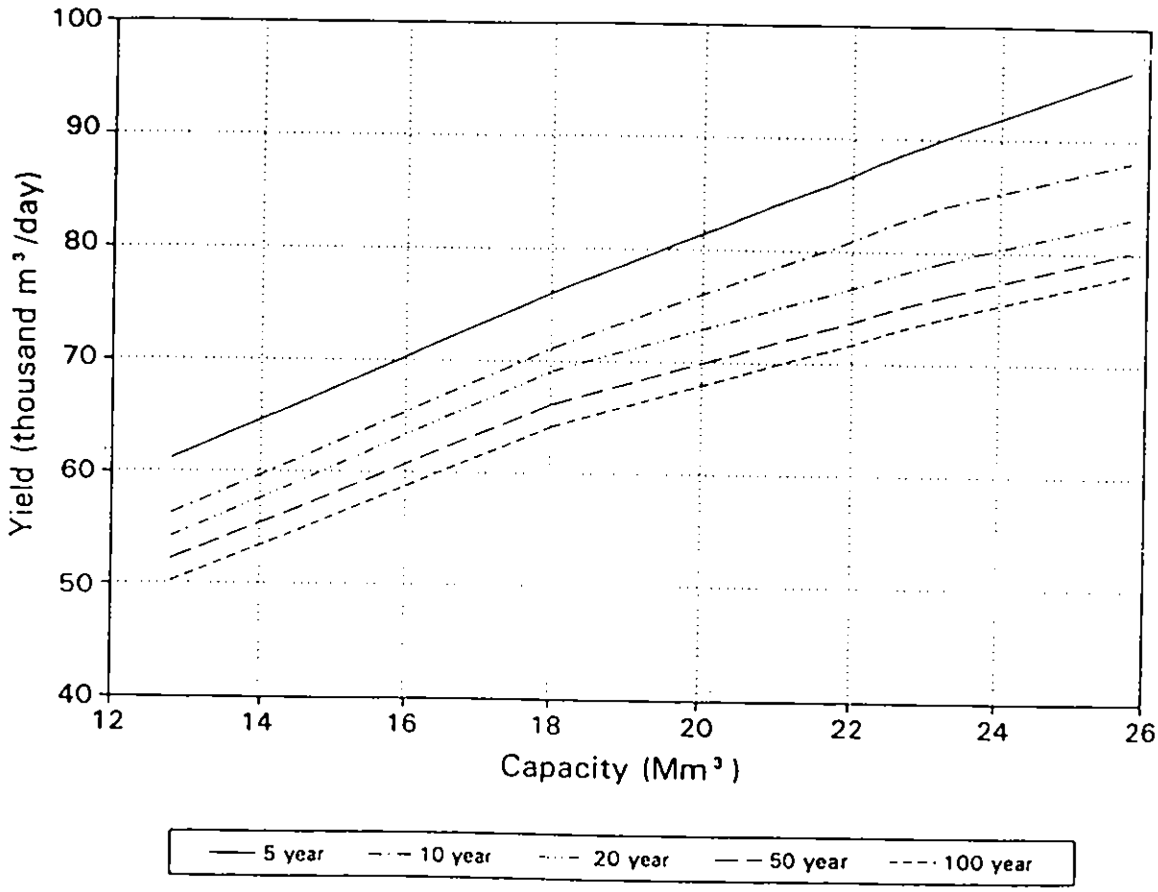

Figure 3.16 Summary of initial results of reservoir yield analysis for Mindu Dam (after compensation flow release of 16000m³/day)

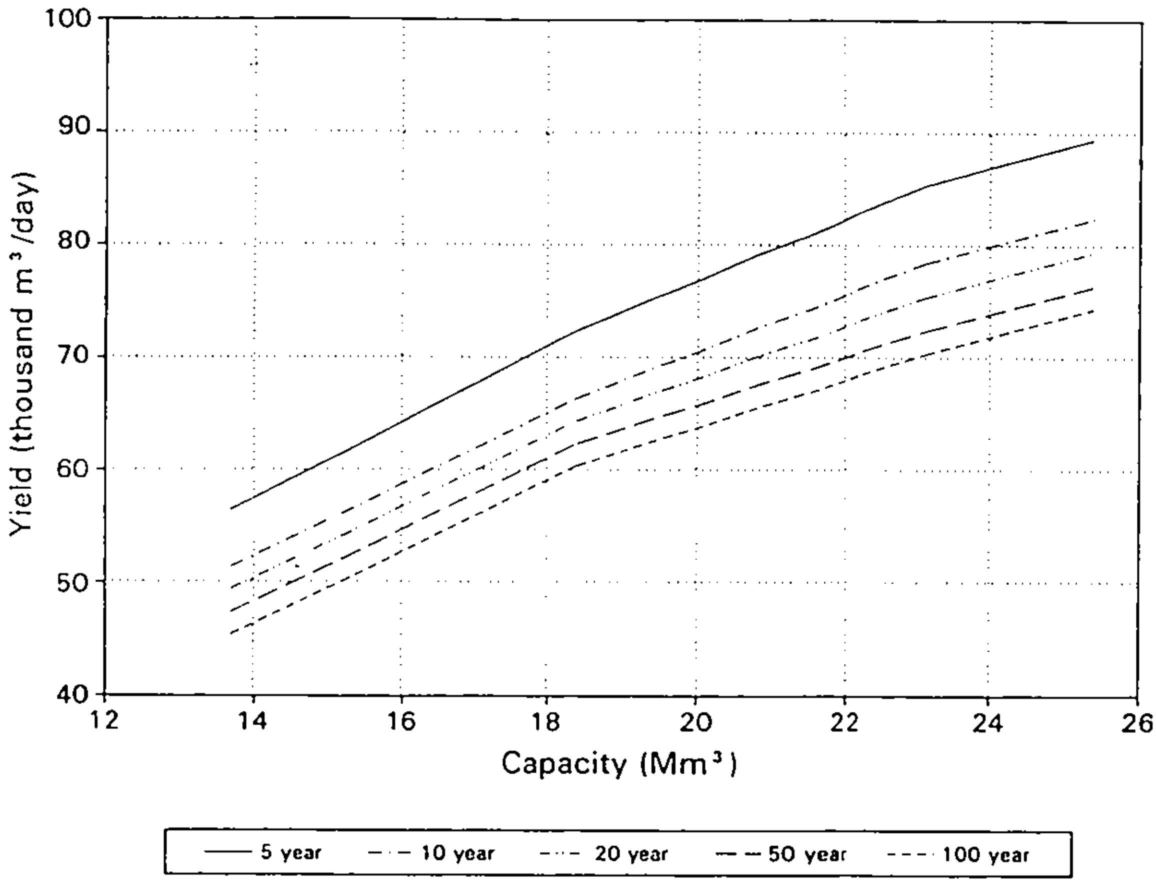

Figure 3.17 Summary of results after 20 years sedimentation of reservoir yield analysis for Mindu Dam (after compensation flow release of 16000m³/day)

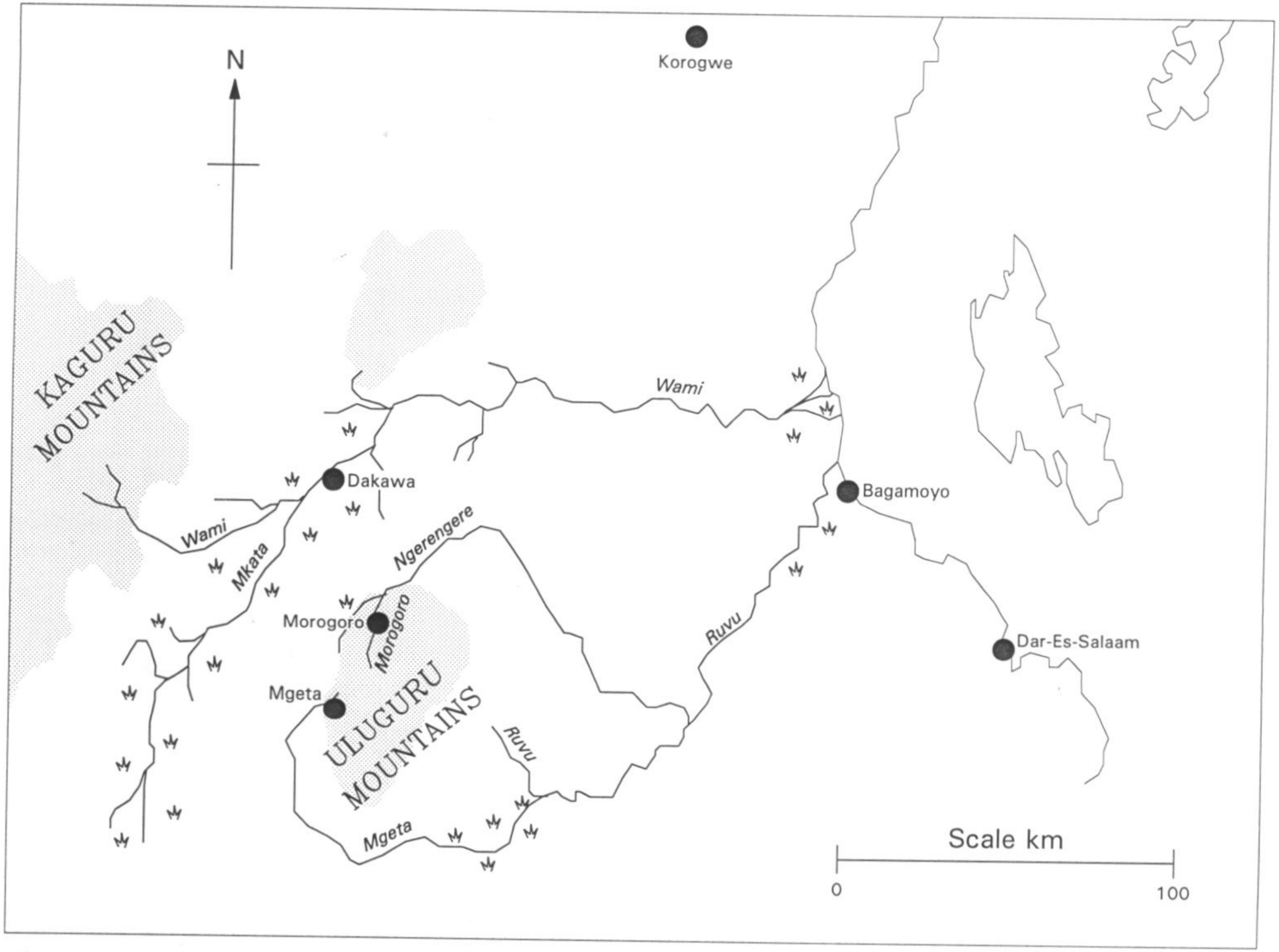

Figure 3.18 *Location map showing Morogoro, Mgeta and Wami rivers*

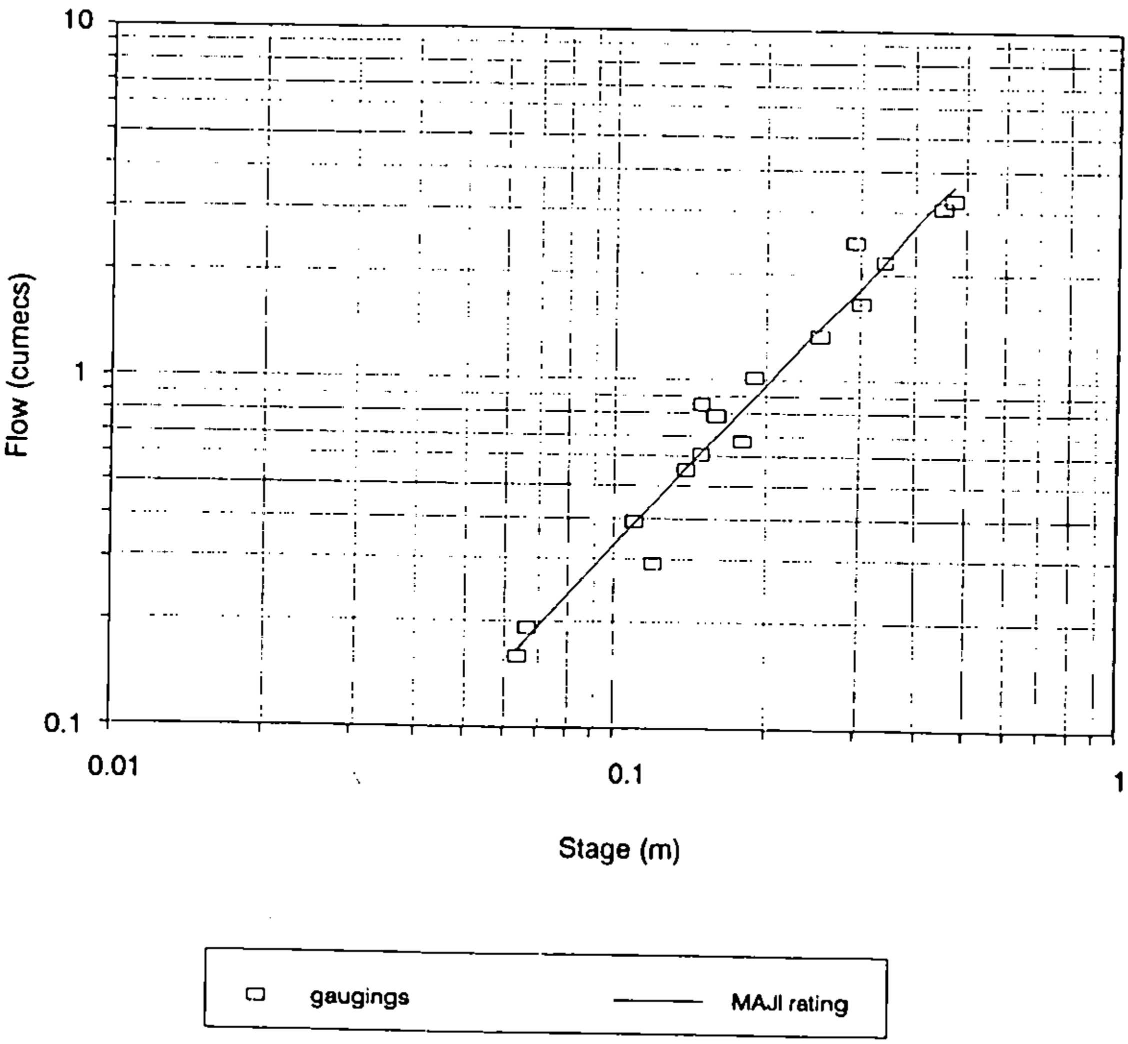

***Figure 3.19** Current meter measurements for Morogoro at Morogoro and MAJI rating*

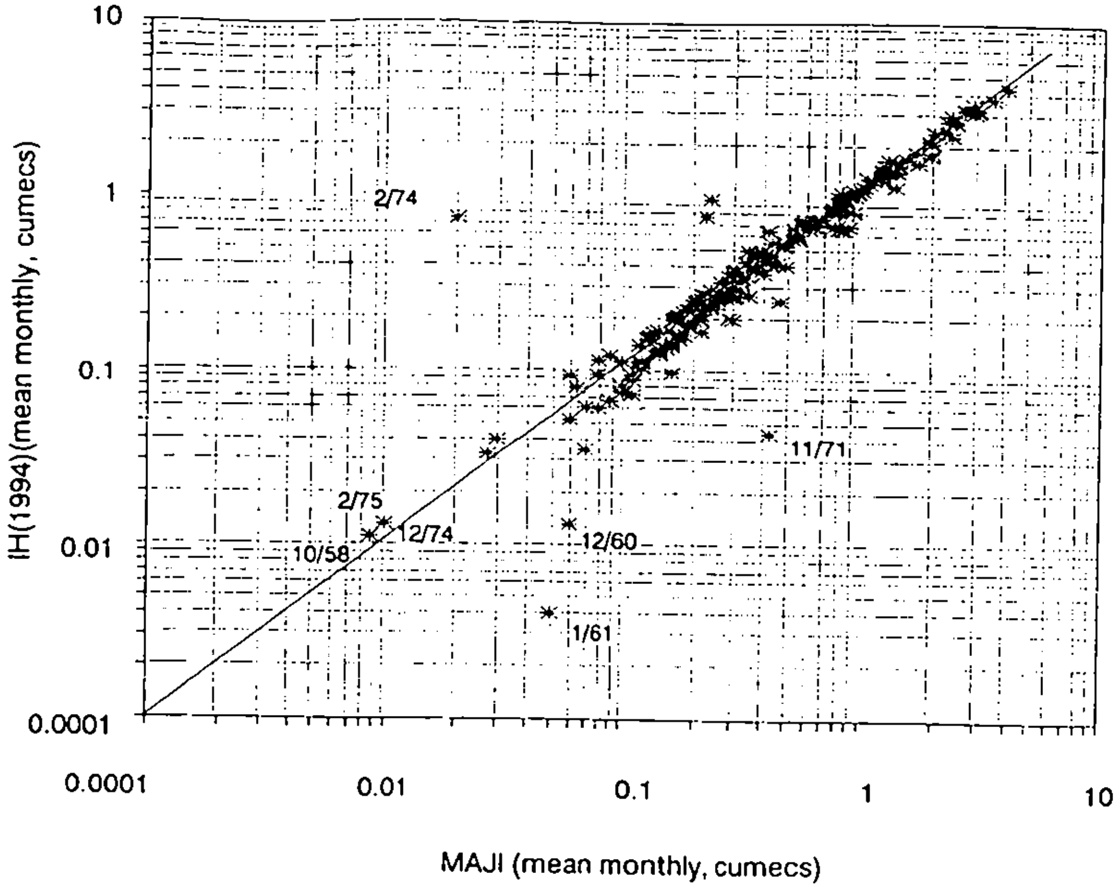

***Figure 3.20a** Comparison of IH (1994) and published MAJI flows for Morogoro at Morogoro*

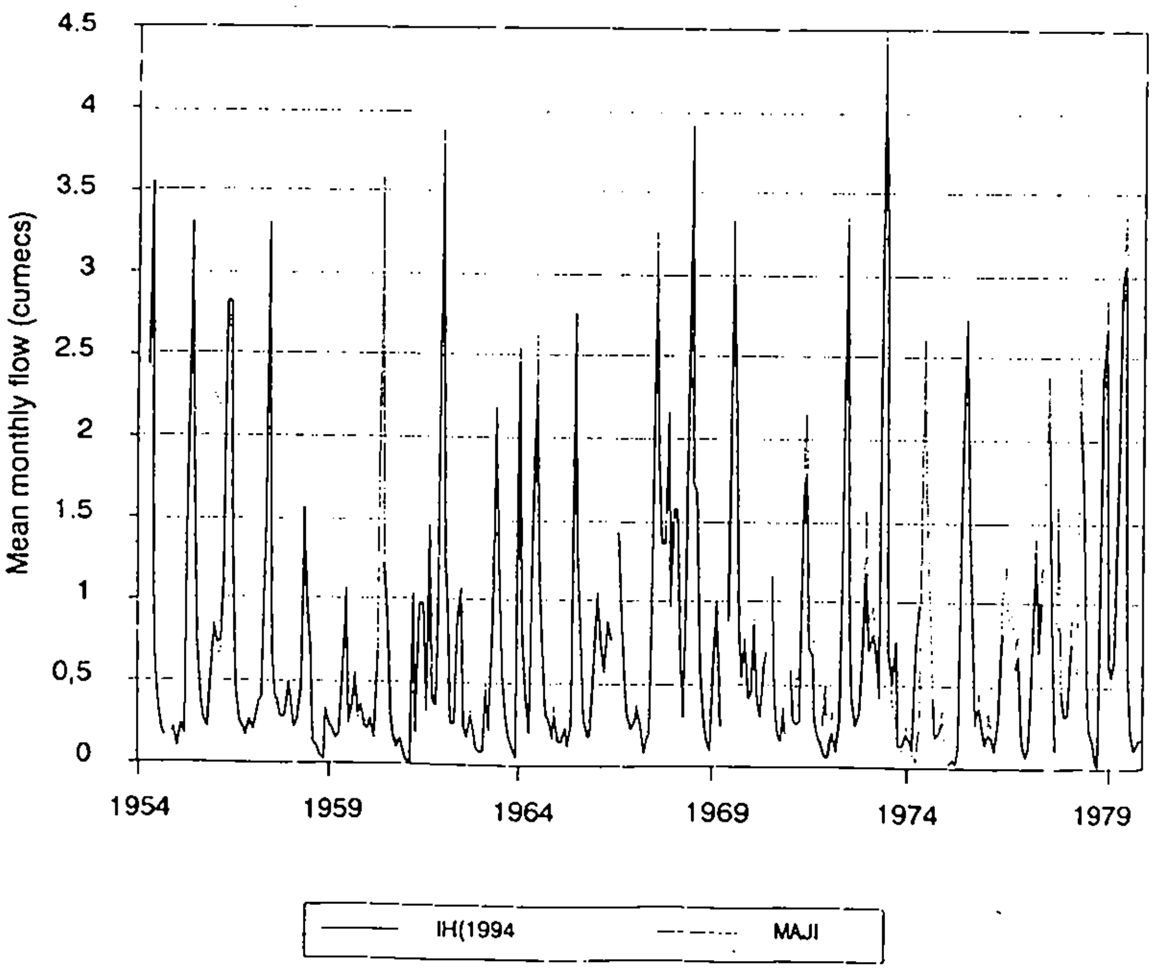

***Figure 3.20b** Comparison of IH(1994) and published MAJI flows for Morogoro at Morogoro*

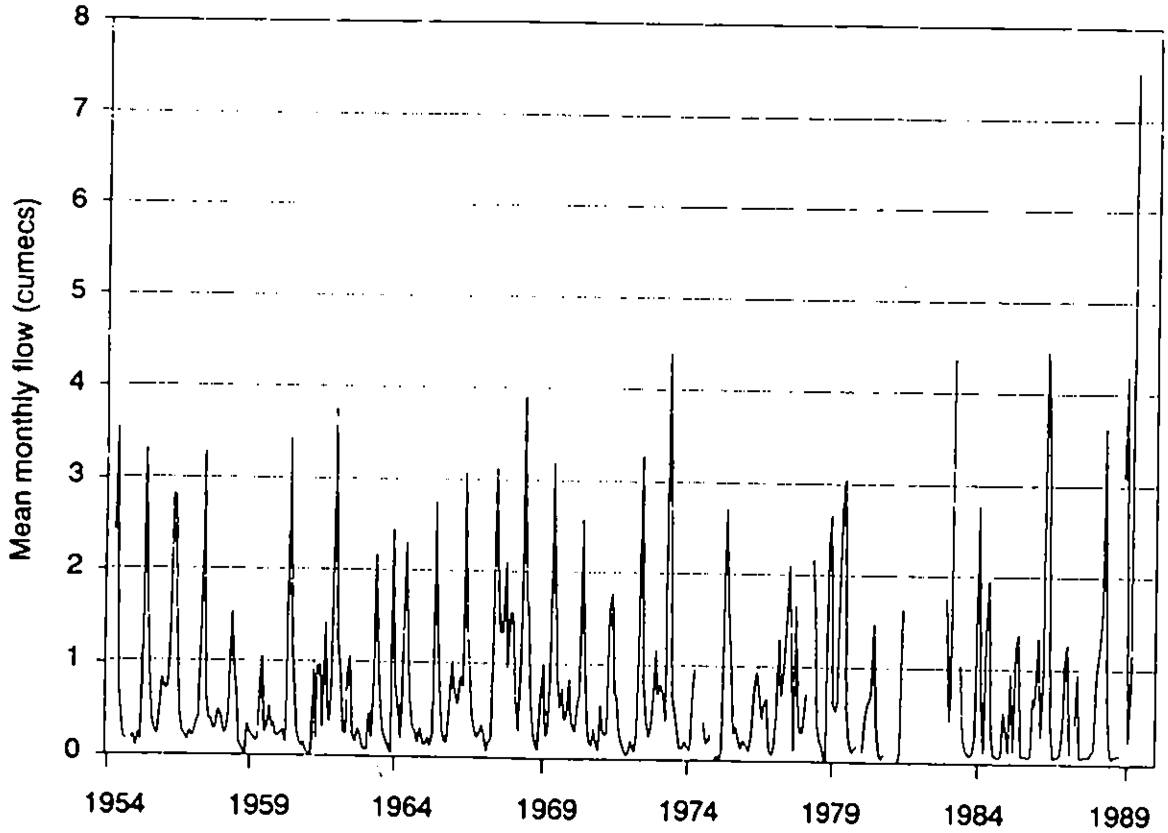

Figure 3.21 *IH(1994) flow series for Morogoro at Morogoro*

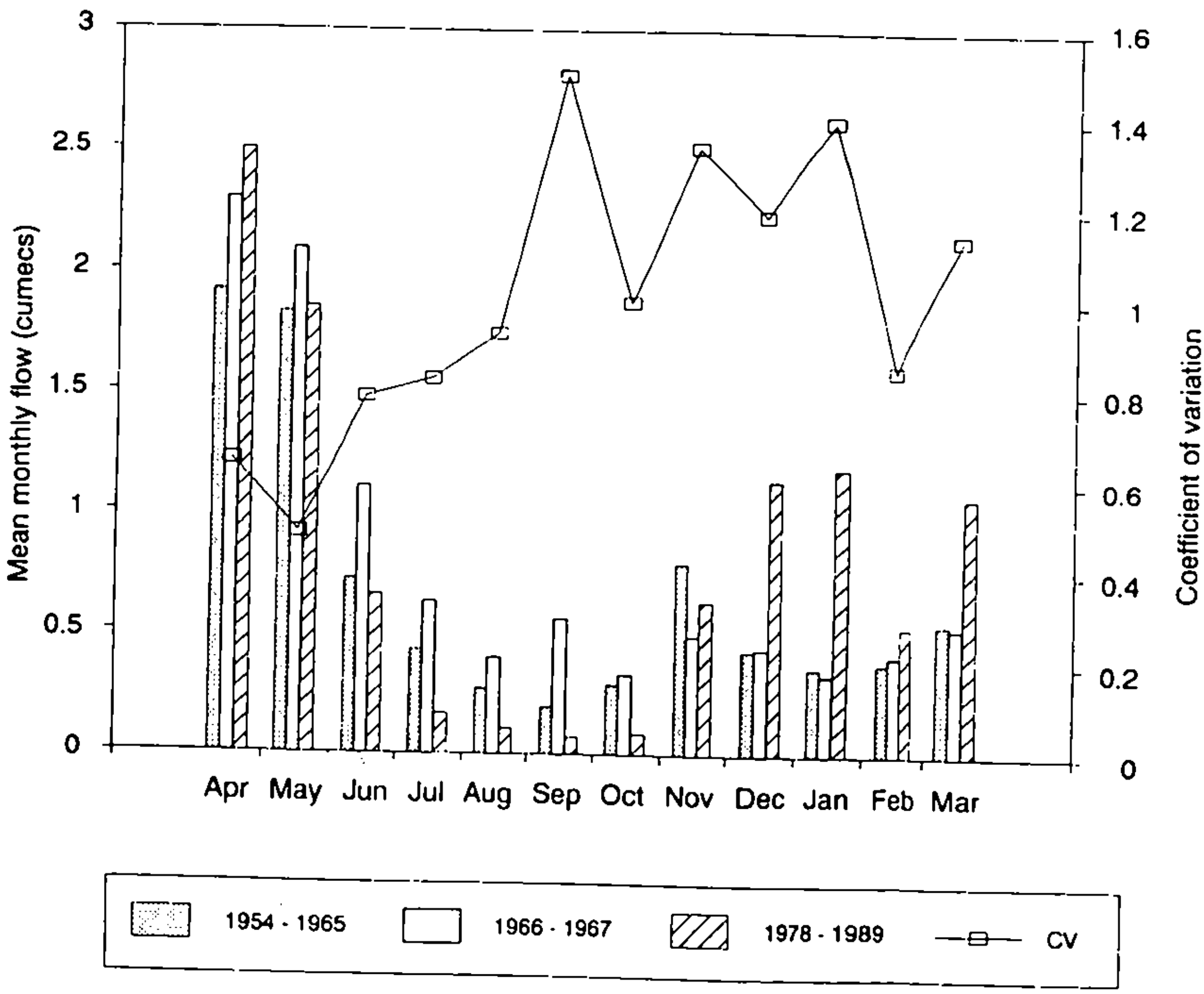

Figure 3.22 *Comparison of mean monthly flows for Morogoro at Morogoro*

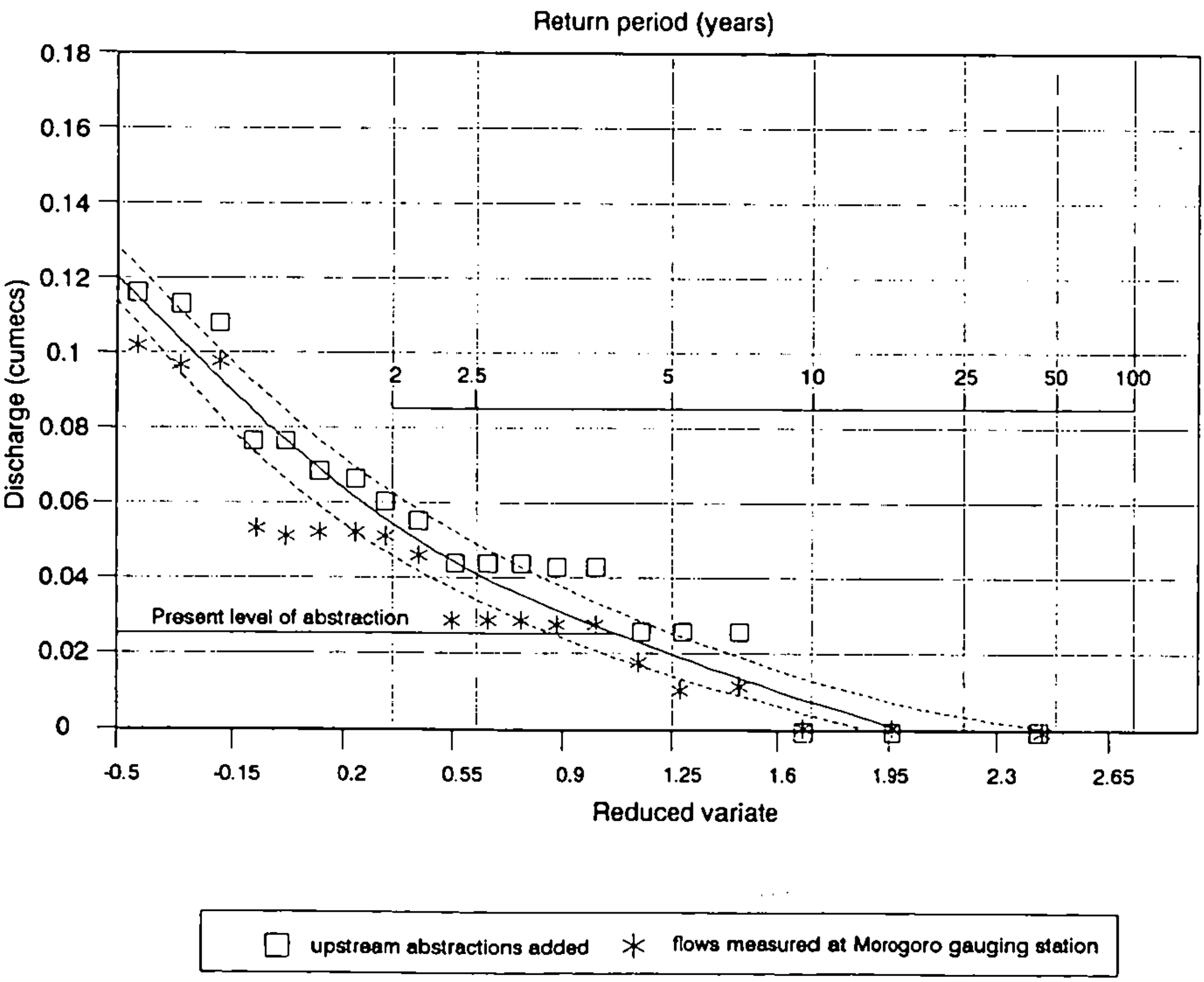

Figure 3.23 *1 day minima for Morogoro at Morogoro*

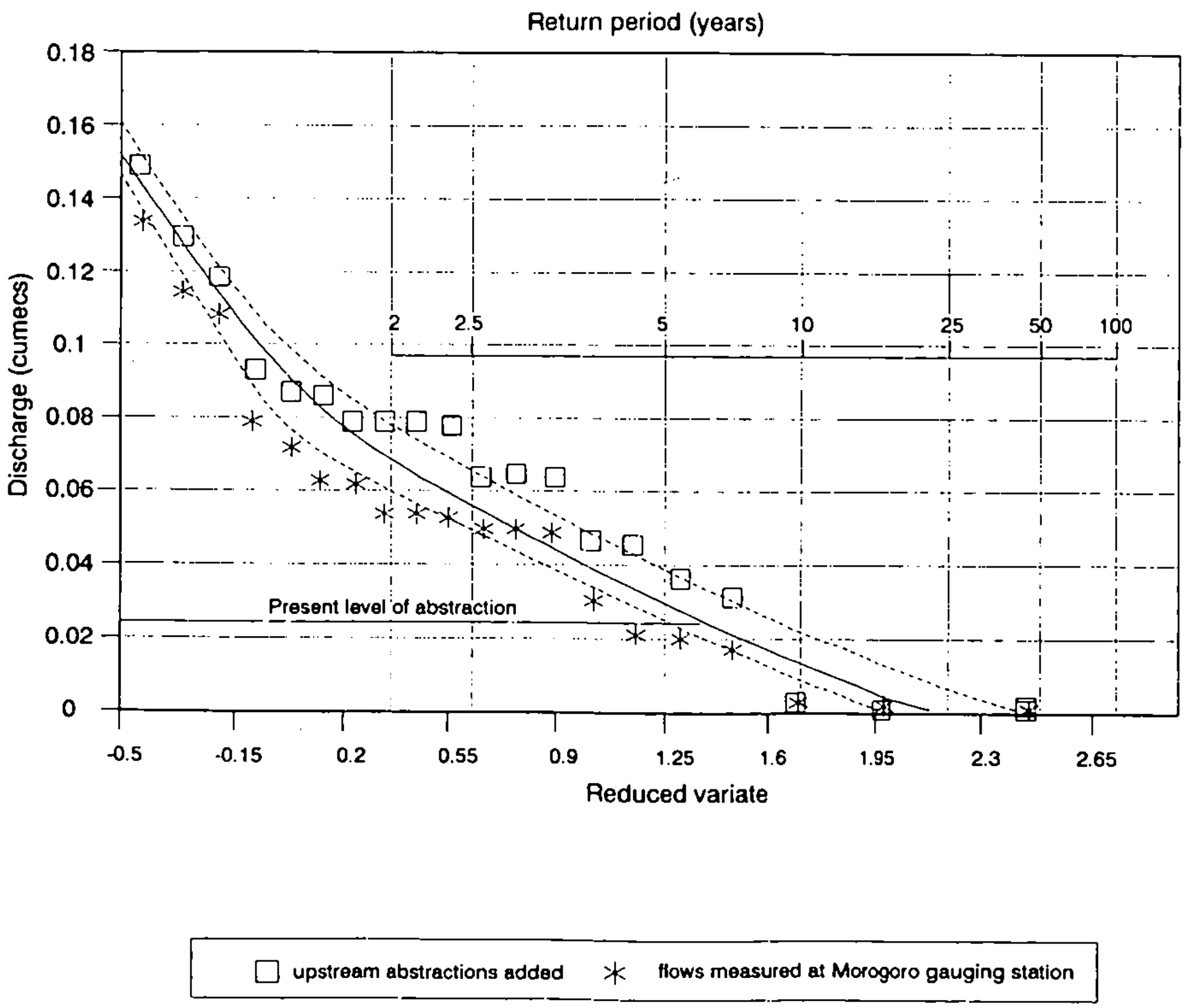

***Figure 3.24** 10 day minima for Morogoro at Morogoro*

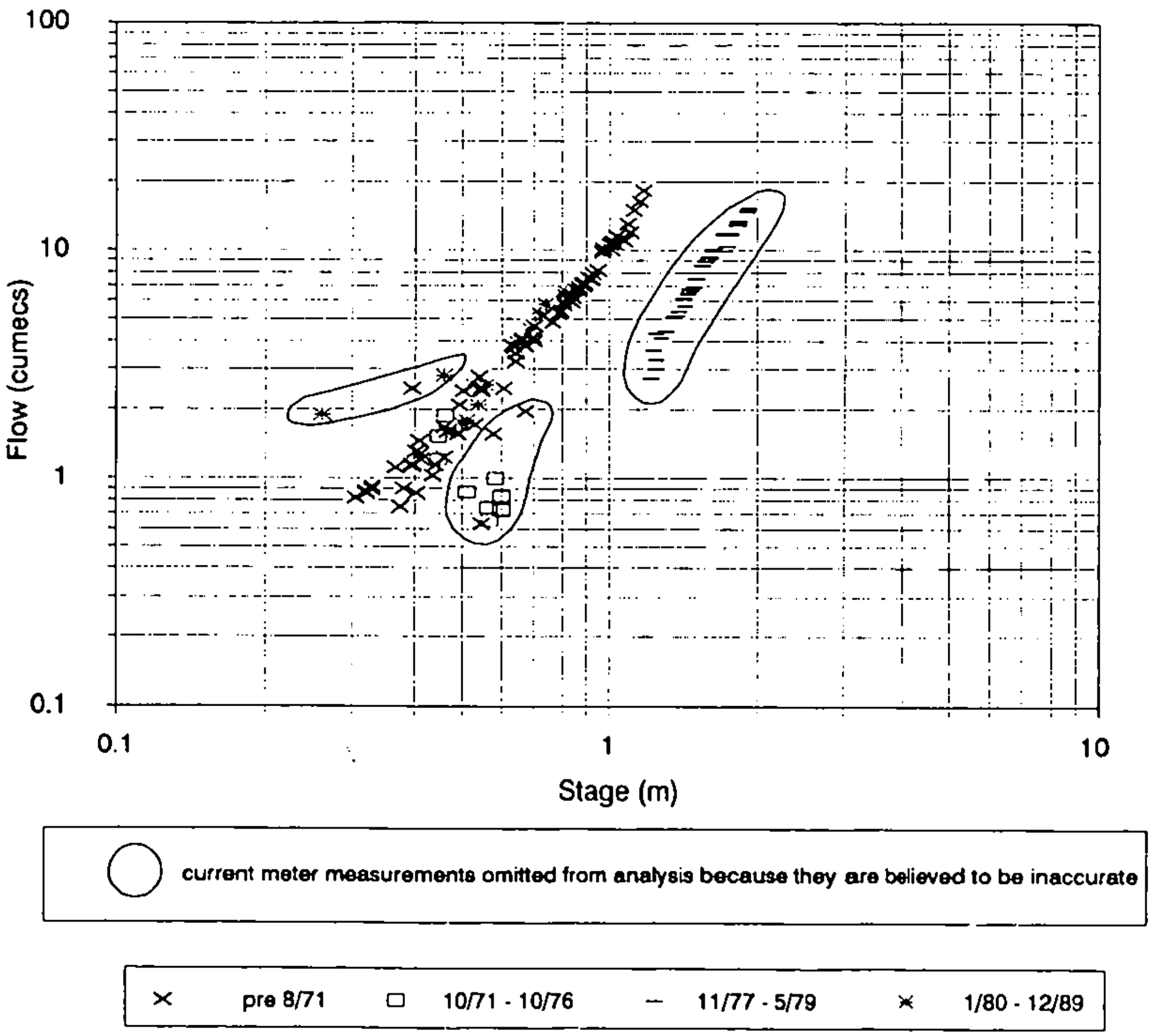

***Figure 3.25** Current meter measurements for Mgeta at Mgeta*

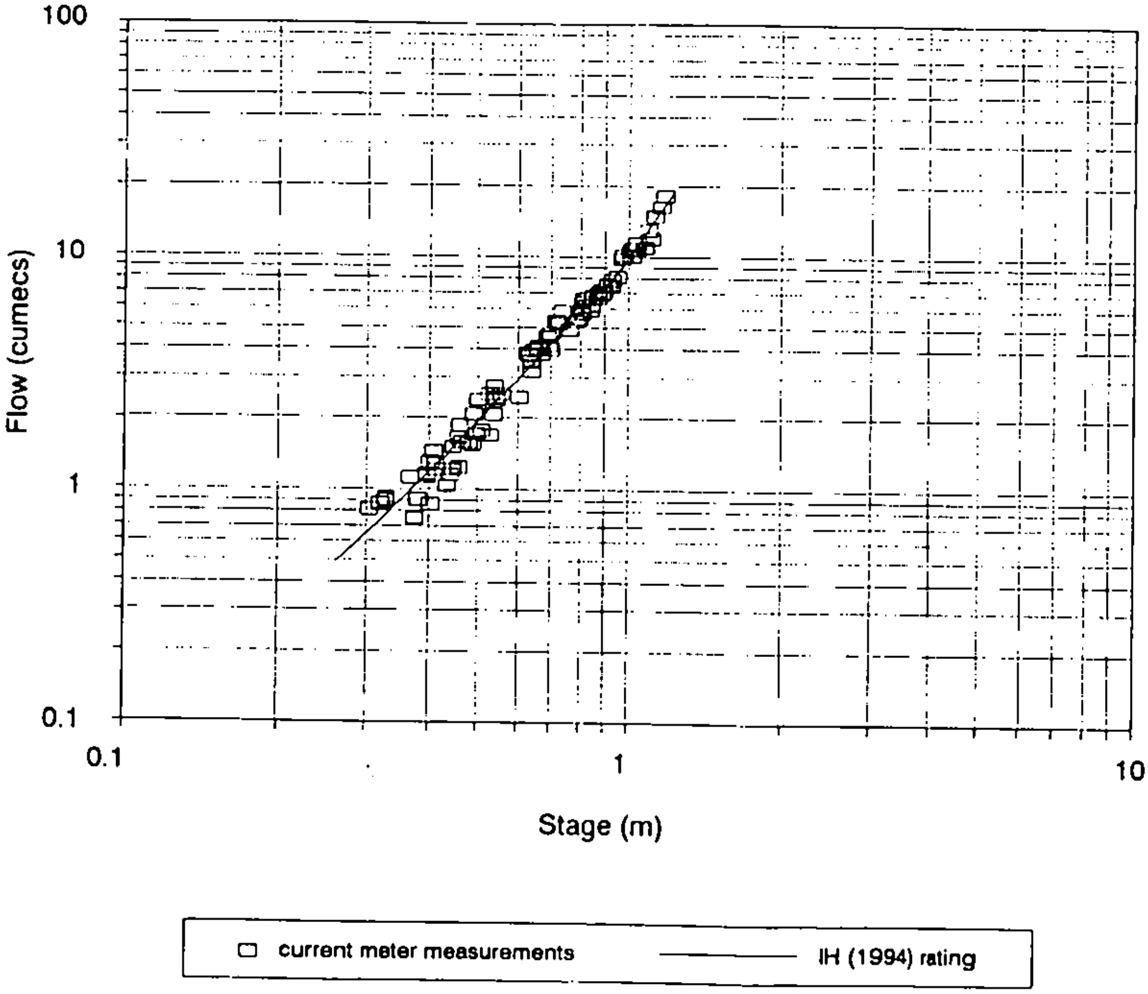

Figure 3.26 Rating equation for Mgeta at Mgeta

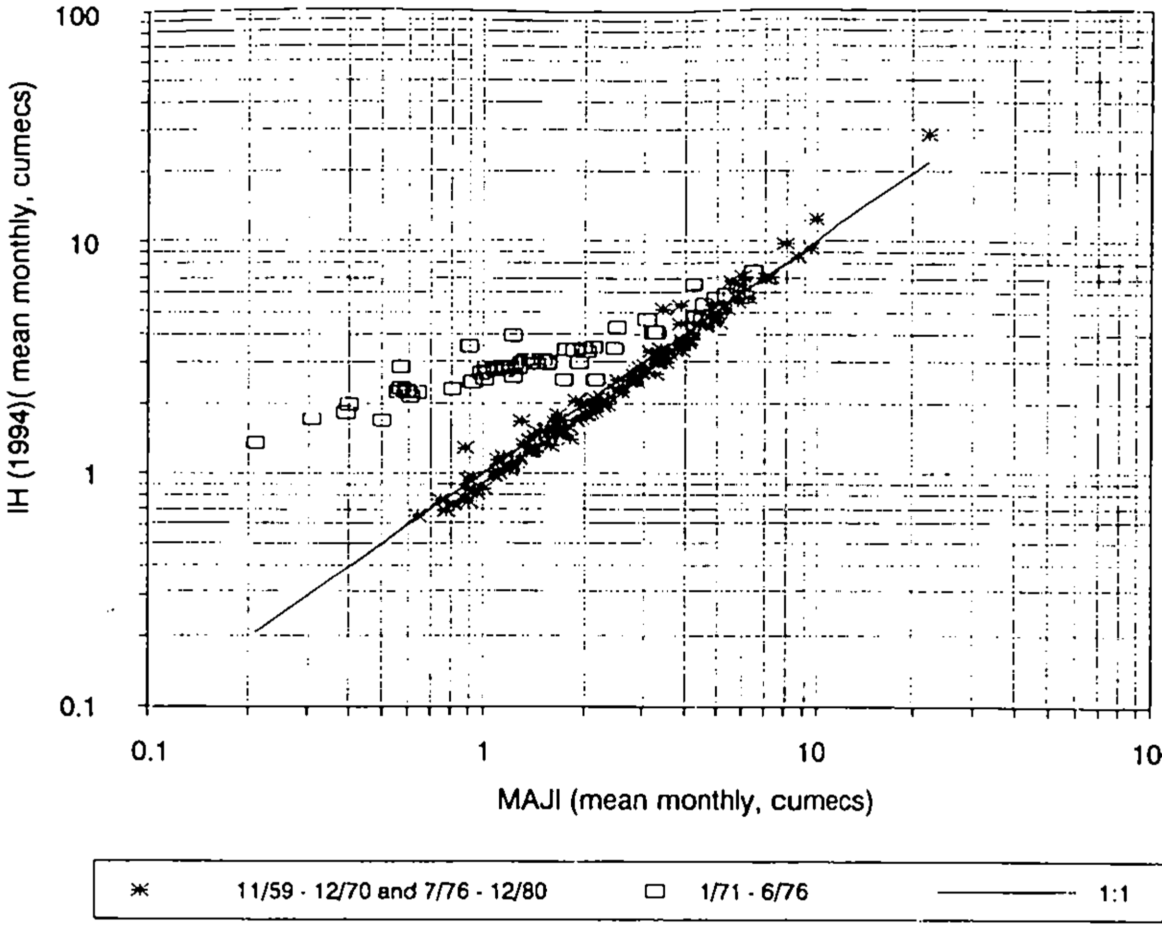

Figure 3.27a *Comparison of IH (1994) and published MAJI flows for Mgeta at Mgeta*

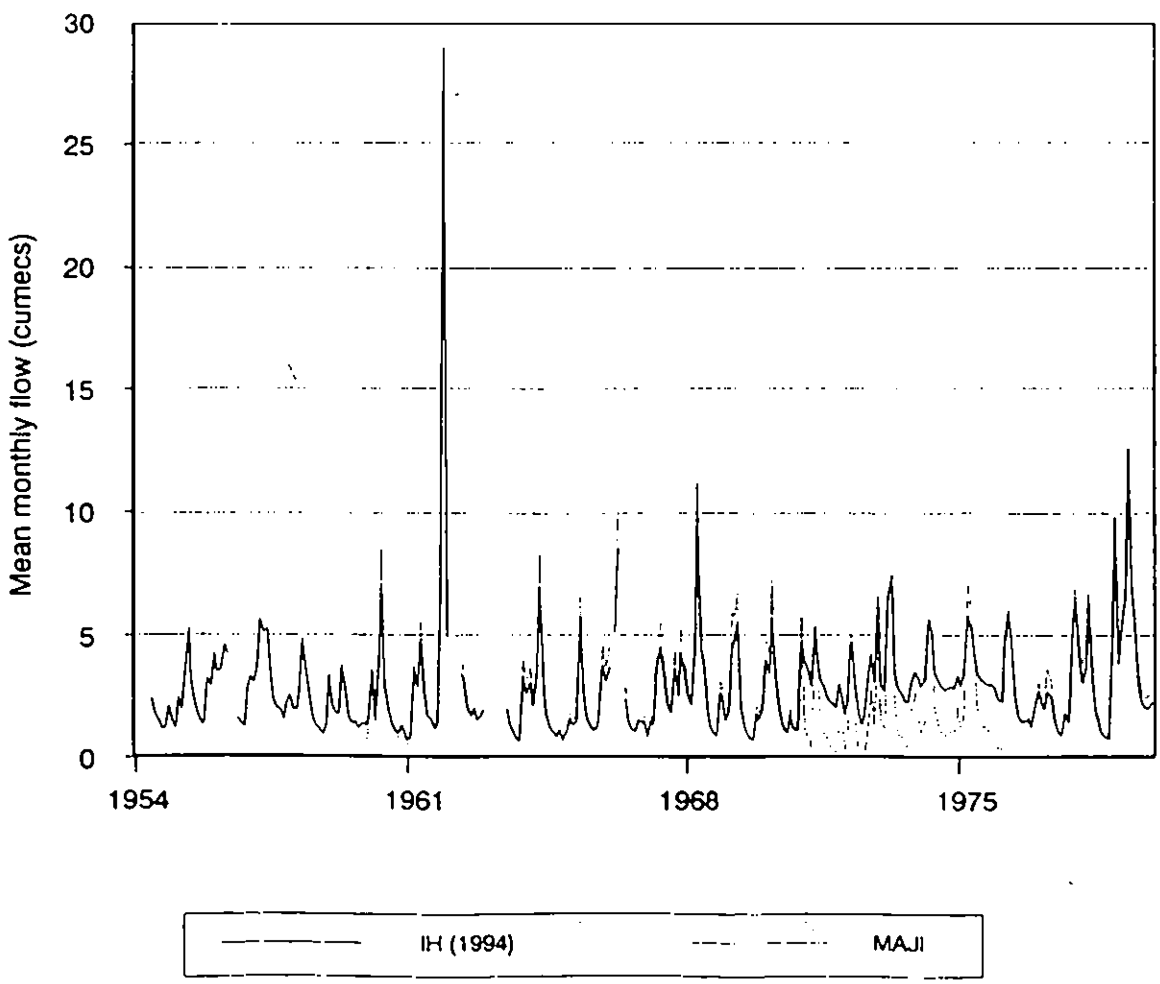

Figure 3.27b *Comparison of IH (1994) and published MAJI flows for Mgeta at Mgeta*

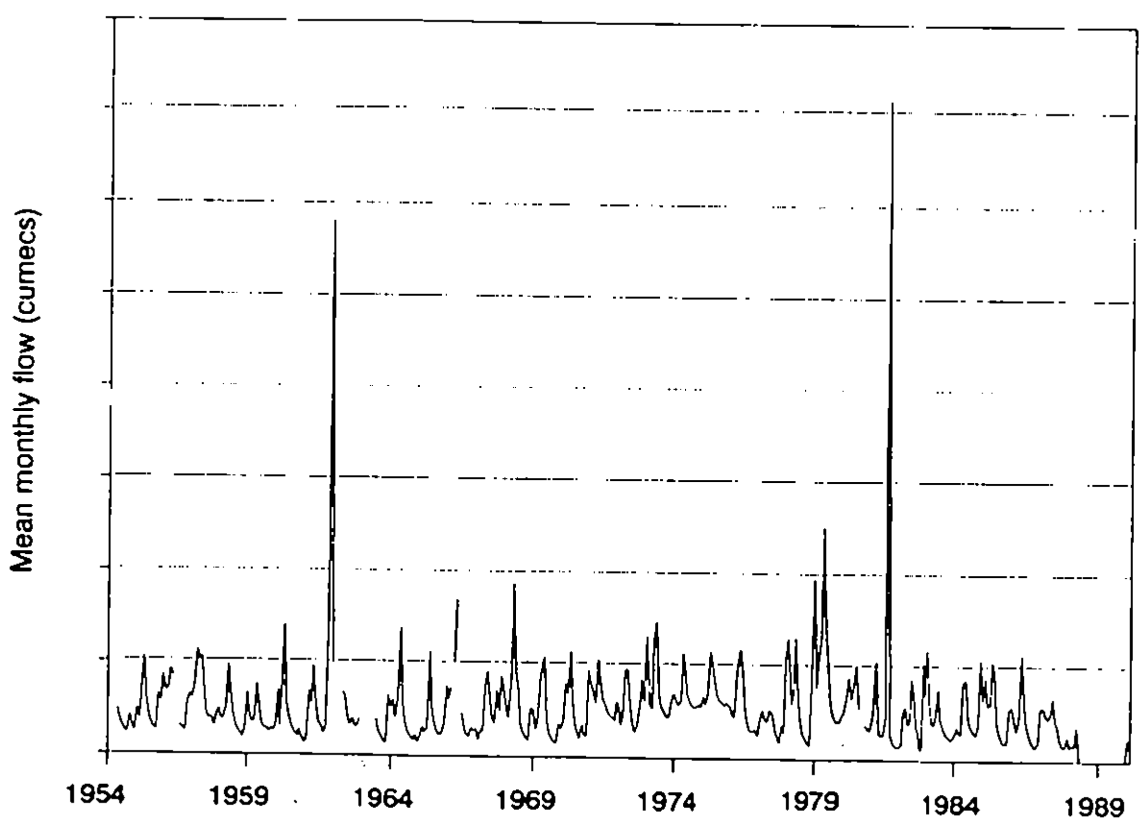

Figure 3.28 *IH(1994) flow series for Mgeta at Mgeta*

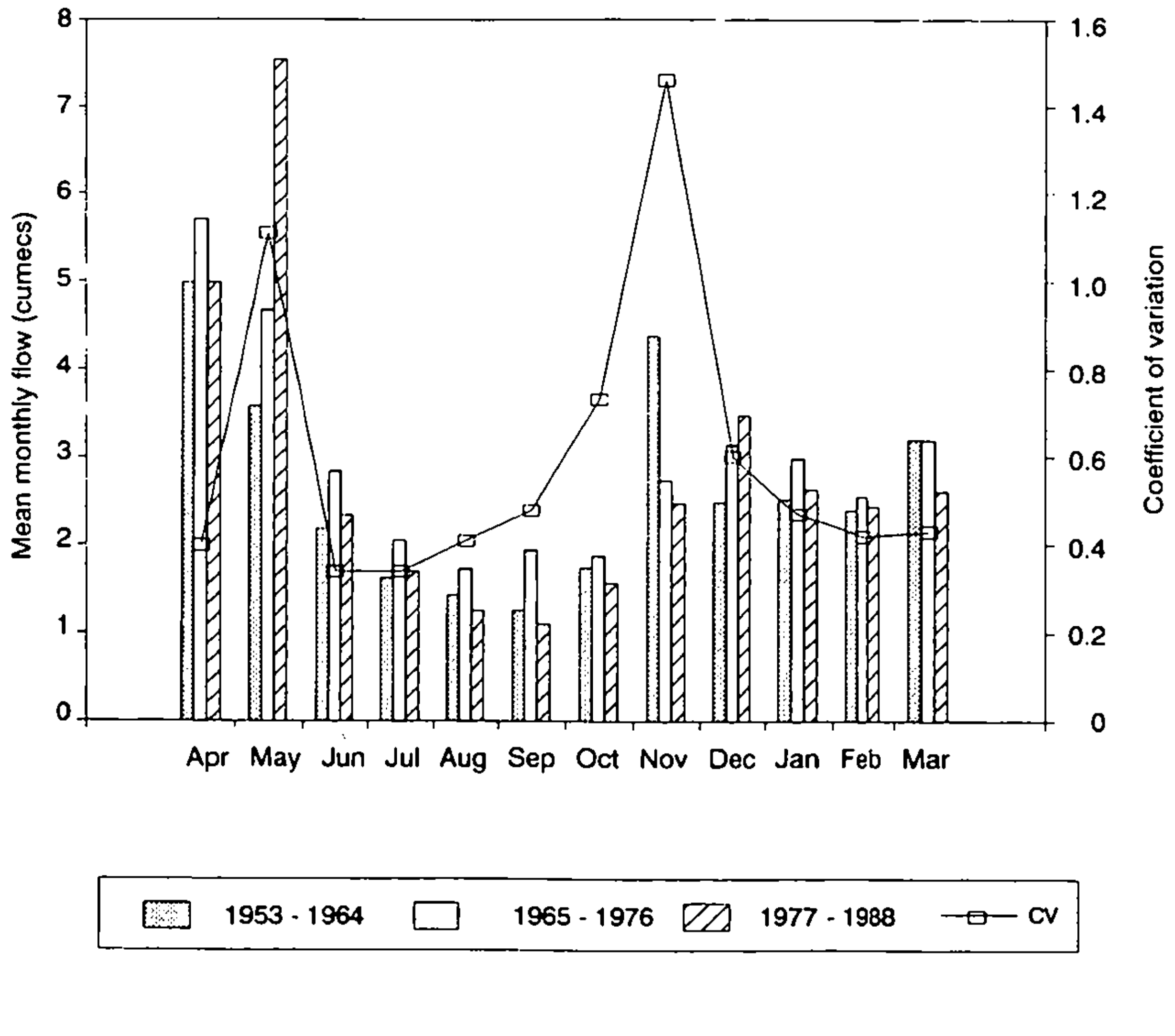

Figure 3.29 *Comparison of mean monthly flows for Mgeta at Mgeta*

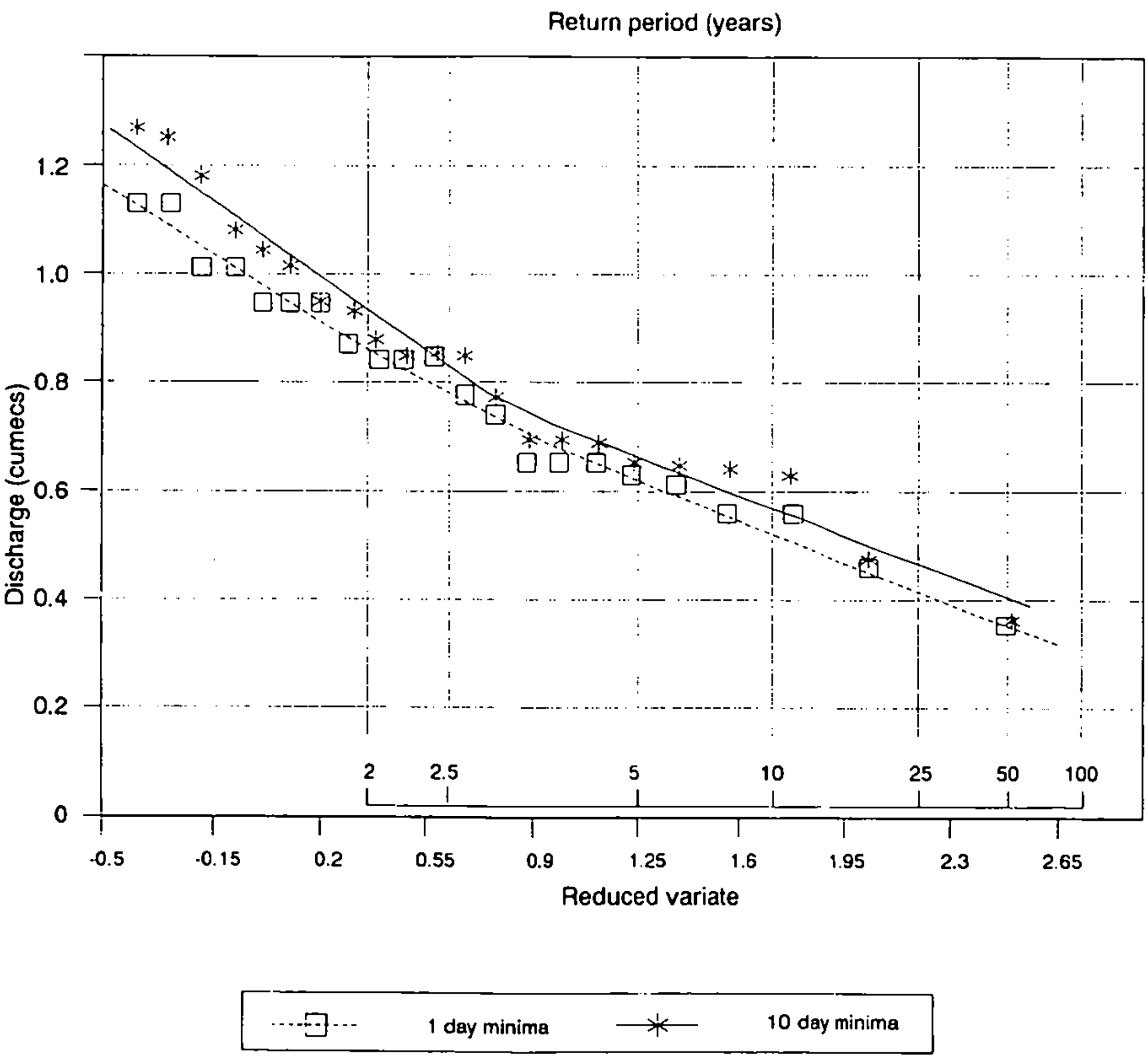

Figure 3.30 *Low flow frequency curves for Mgeta at Mgeta*

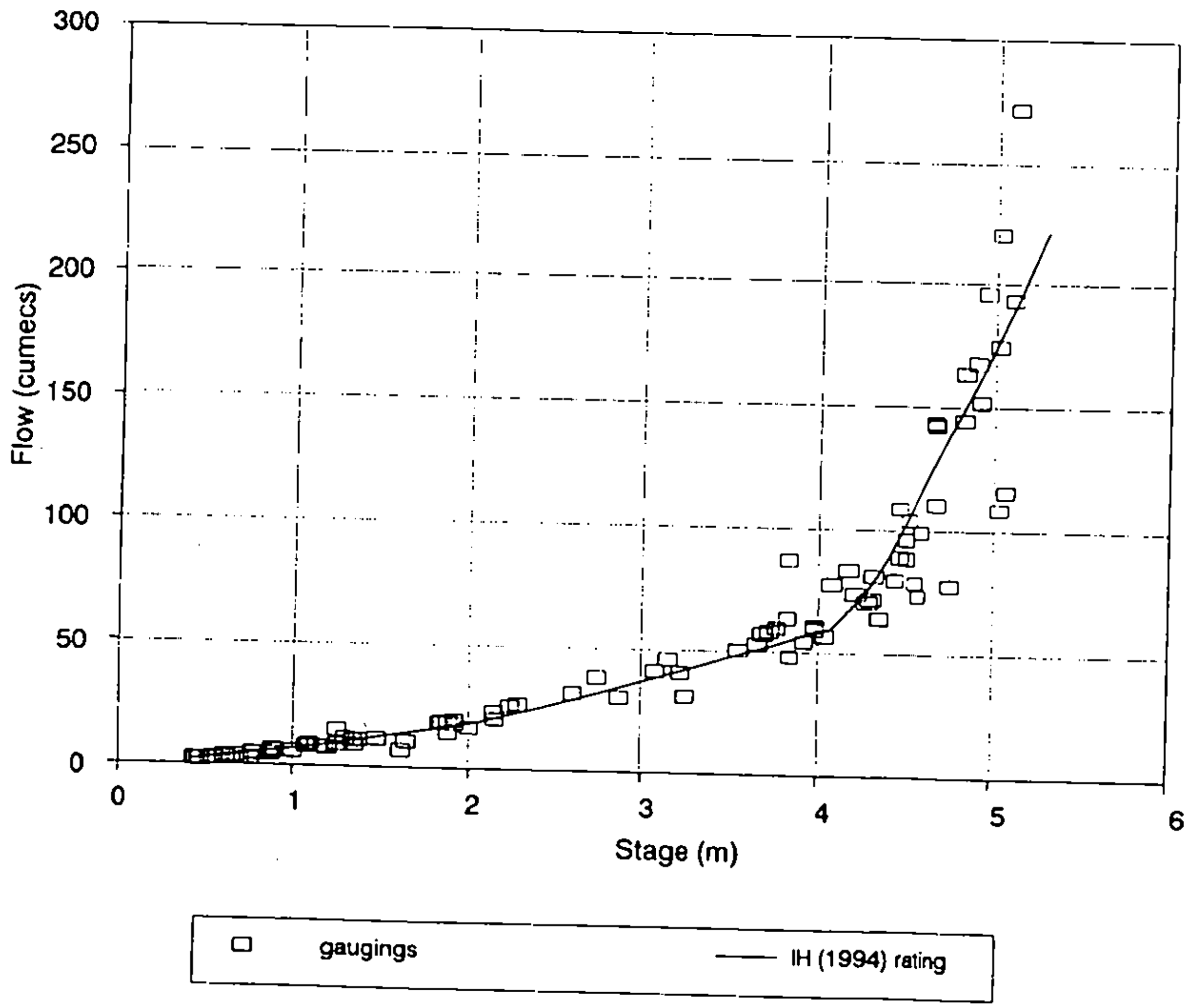

Figure 3.31 *Current meter measurements for Wami and Dakawa and IH(1994) rating*

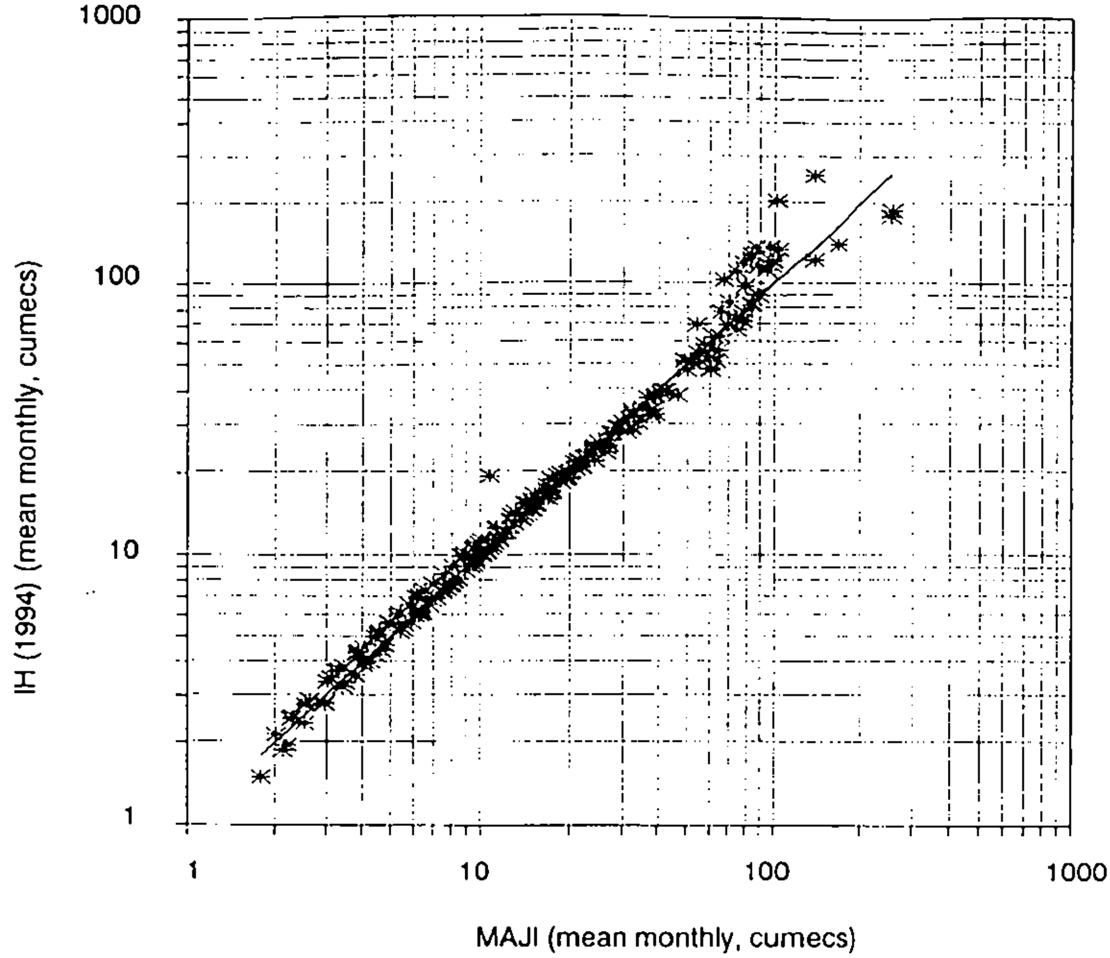

Figure 3.32a *Comparison of IH (1994) and published MAJI flows for Wami at Dakawa*

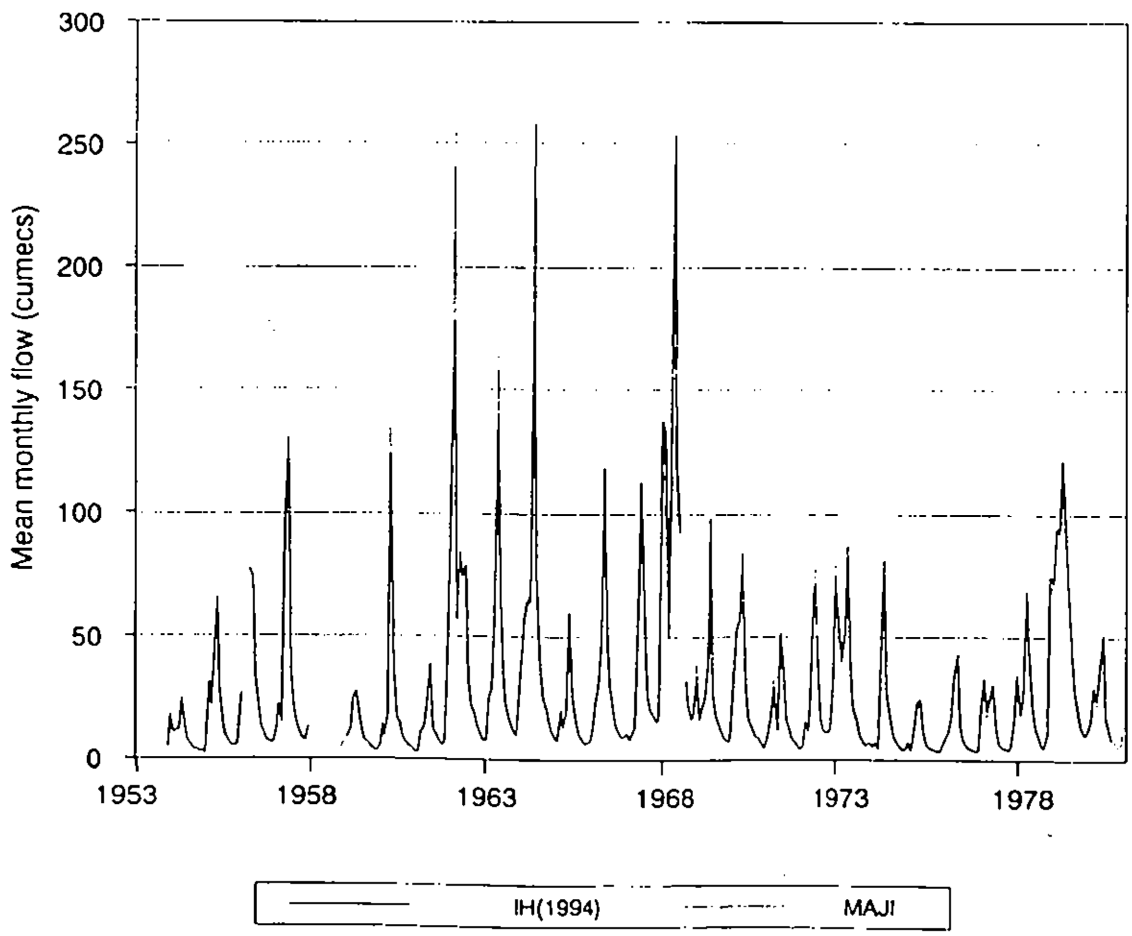

Figure 3.32b *Comparison of IH (1994) and published MAJI flows for Wami at Dakawa*

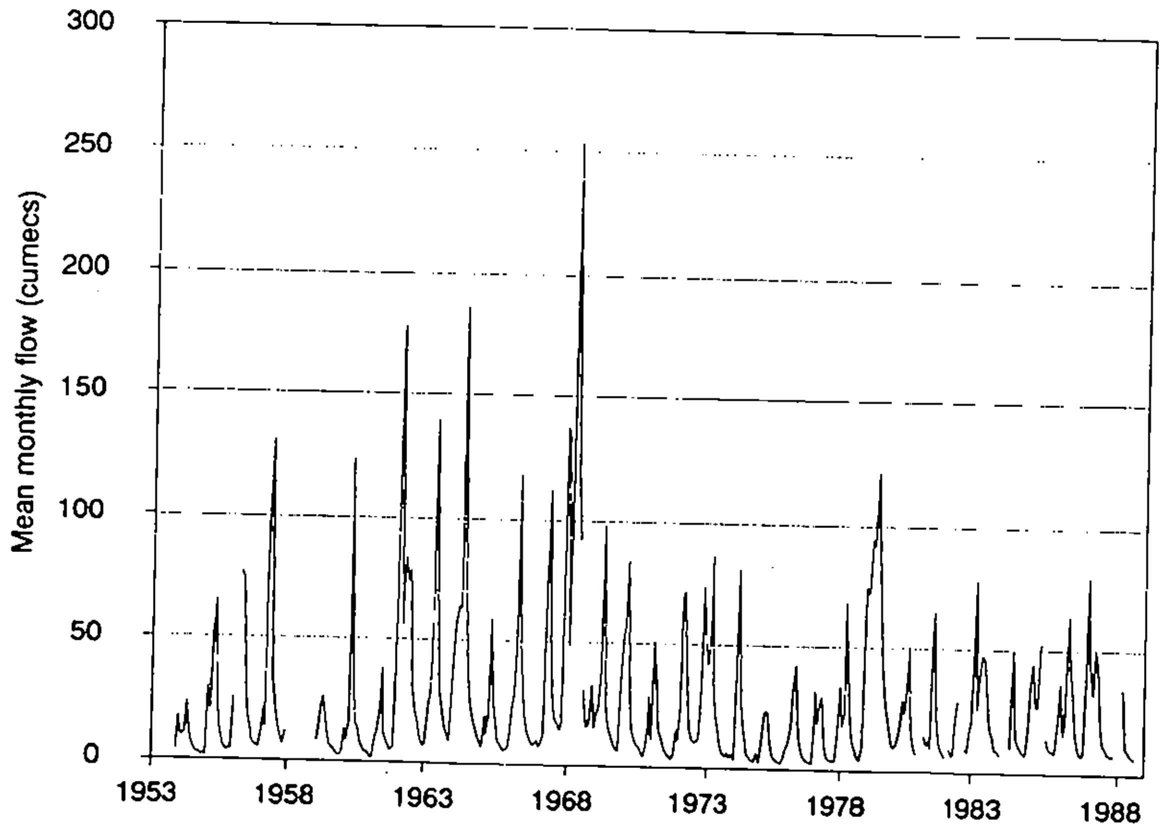

Figure 3.33 *IH(1994) flow series for Wami at Dakawa*

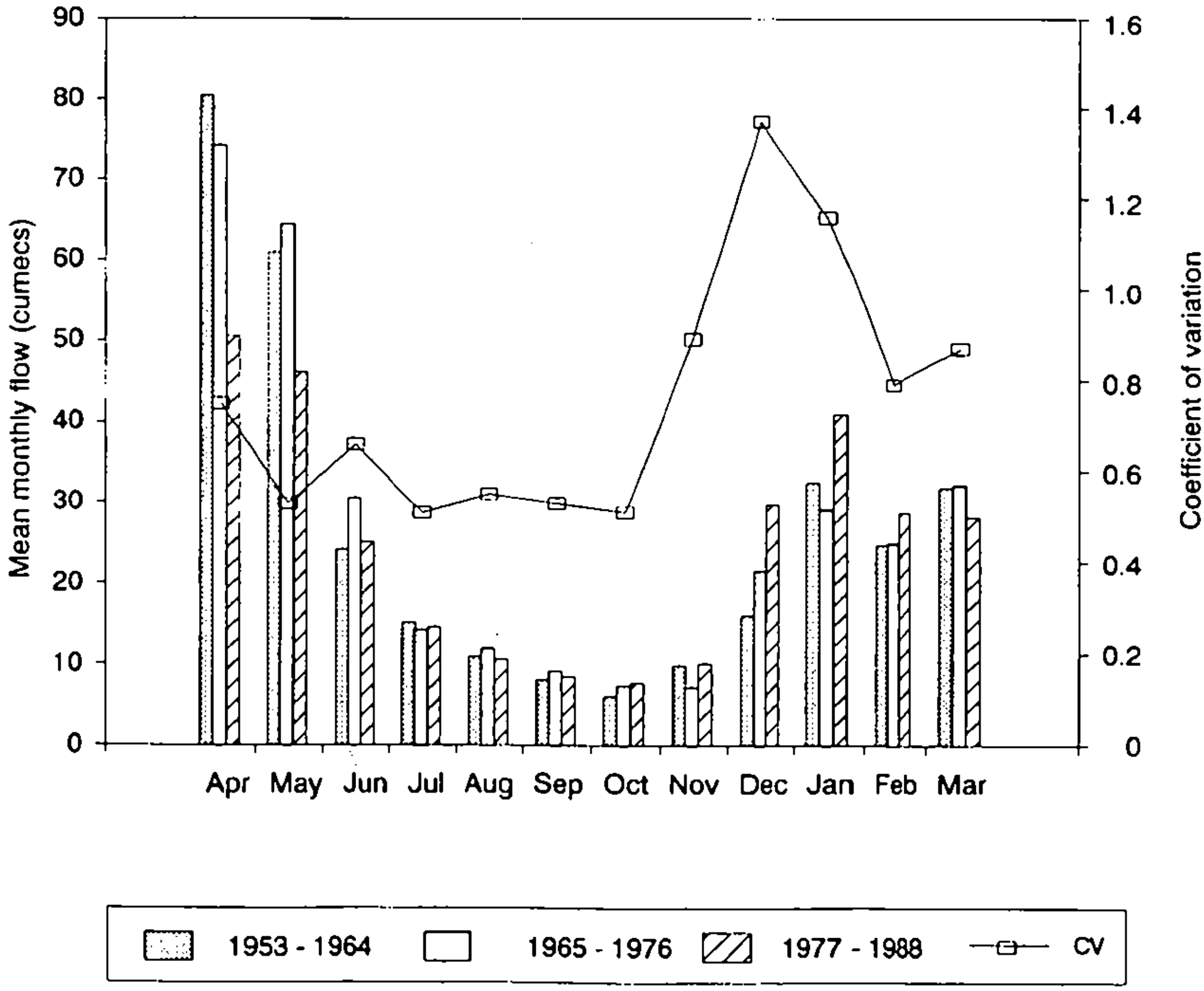

Figure 3.34 *Comparison of mean monthly flows for Wami at Dakawa*

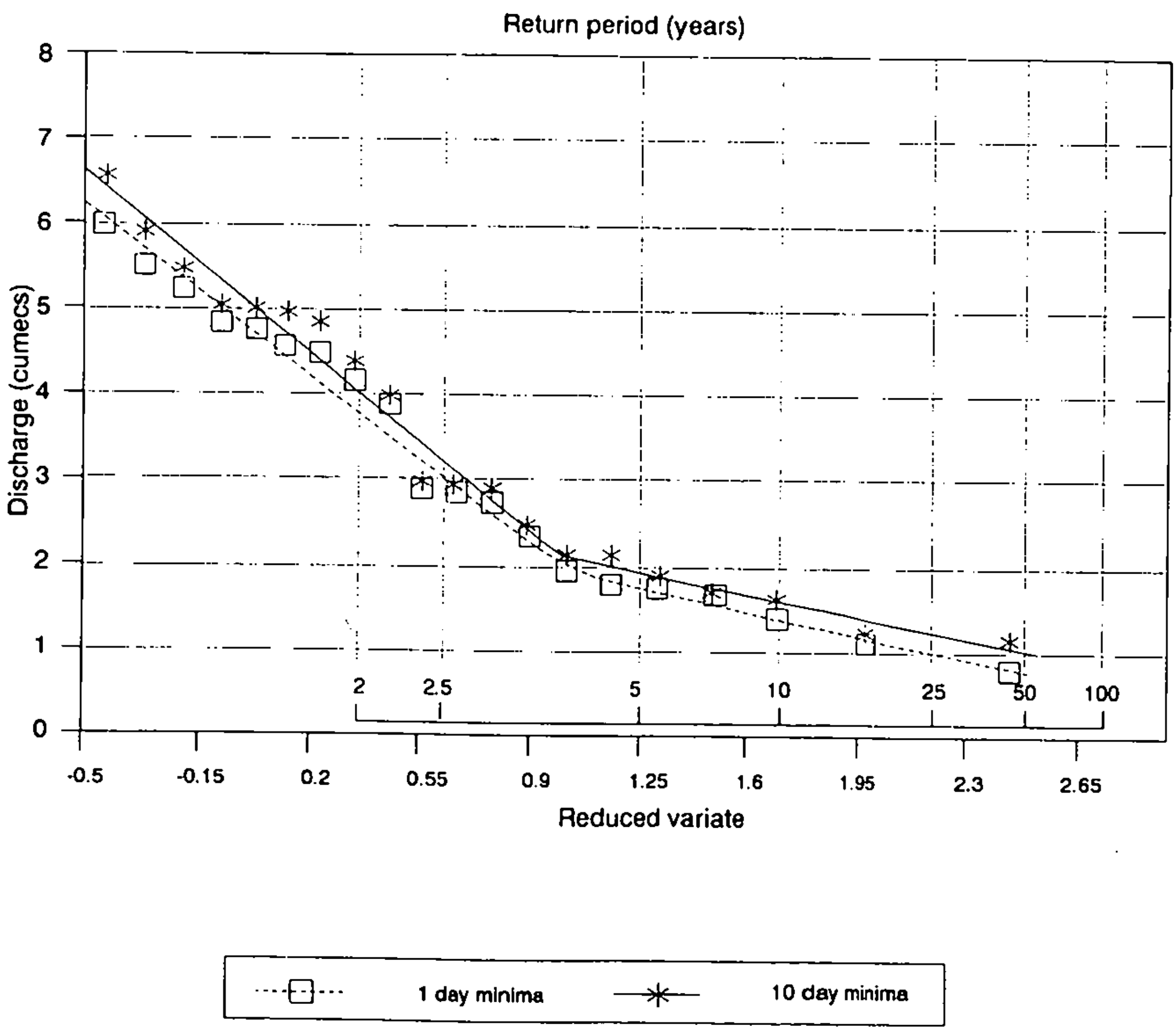

Figure 3.35 *Low flow frequency curves for Wami at Dakawa*

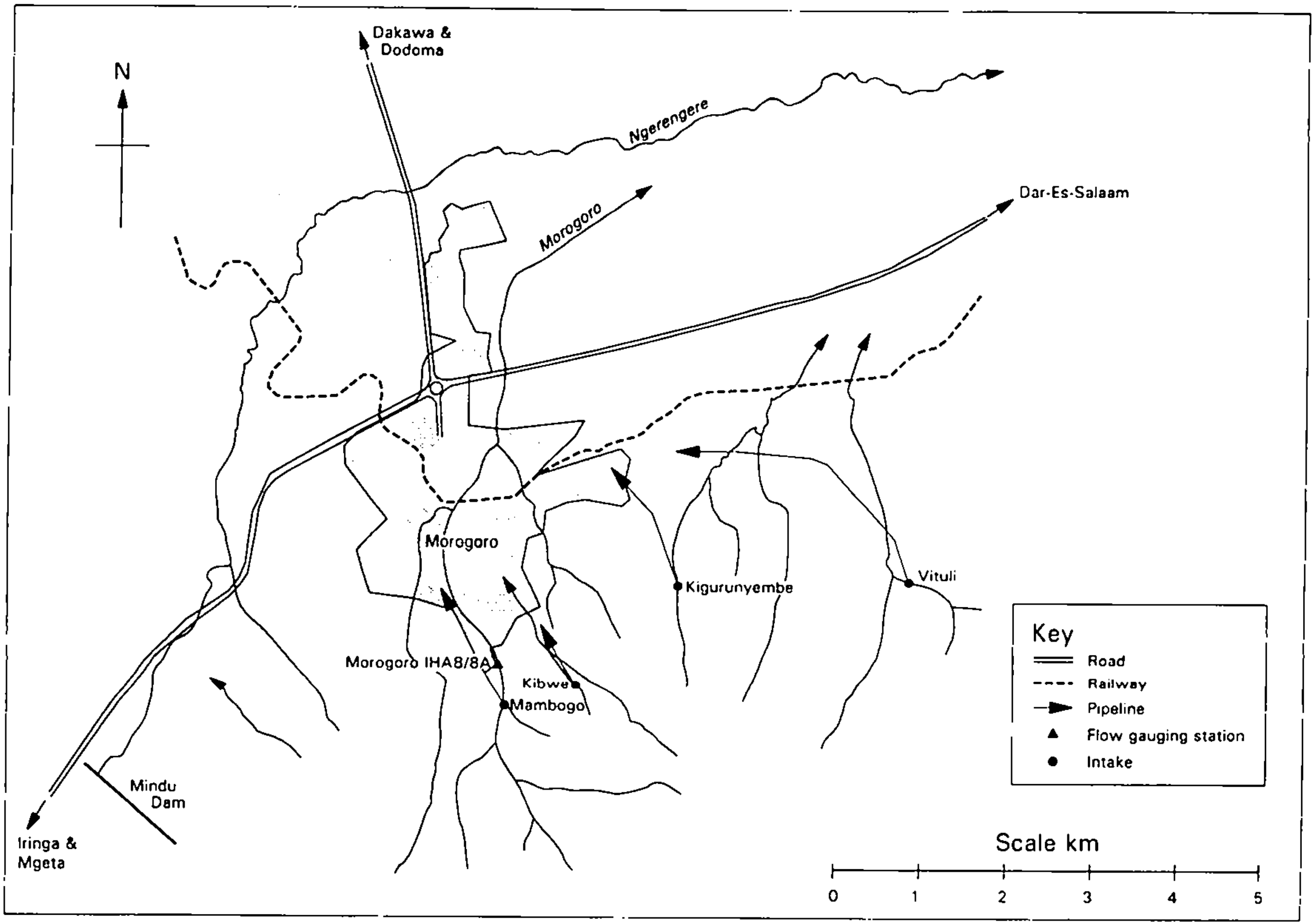

Figure 3.36 *Location map showing spring sources at Kibwe, Kigurunyembe and Vituli*

Acknowledgements

The Ministry of Water, Energy and Minerals (MAJI) is responsible for the collection of hydrological data. The collection of meteorological data is the responsibility of the Directorate of Meteorology. We would like to thank staff at MAJI Ubungo, MAJI Morogoro and the Directorate of Meteorology for their assistance and helpful discussions during the data collection phase of the study.

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Appendix A

Table A.1 Mean monthly flows for Morogoro at Morogoro

Institute of Hydrology
Summary of monthly data - Flow

Station number : 218 Name : Morogoro at Morogoro

Basin no. : 0 Latitude 6.51: 0 N Longitude : 37 40 0 E Altitude : 543.0
Area : 23.3

	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Annual Mean
1954/55	2.42	3.55	.71	.38	20	.15	-	.17	.21	.08	.23	.16	-
1955/56	1.67	3.31	1.67	.75	.38	.26	.21	45	.84	.72	.73	1.10	1.01
1956/57	2.82	2.82	1.33	.47	.25	.20	.15	.26	.19	.24	.37	.39	.79
1957/58	1.50	3.30	.67	38	.38	.27	.28	.49	.42	.22	.25	.47	.72
1958/59	1.56	1.02	.70	.11	.09	.03	.01	33	.23	.20	14	.17	.38
1959/60	.49	1.07	.24	.33	.55	.30	.36	.21	.20	.26	.13	.67	.40
1960/61	3.44e	1.22	.85	.29	.15	.09	.14	.06	.01	.00	1.04	.18	61
1961/62	.97	.99	31	1.45	.39	.35	.93	3.78	1.28	.88	25	24	.99
1962/63	.86	1.08	23	14	.30	.24	.09	.07	.07	.46	20	.87	.38
1963/64	2.19	1.09	53	.27	.18	.10	.04	2.45	84	.45	18	1.28	.80
1964/65	2.32	1.14	61	30	27	.14	.30	13	.13	21	10	.25	49
1965/66	2.76	1.34	.75	.27	16	.16	.65	1.04	.74	55	.88	76	.83
1966/67	3.09e	1.42	93	.47	.31	.21	.26	34	23	06	16	19	64
1967/68	1.43	1.13	1.86	1.35	1.35	2.13	.97	1.57	1.56	.60	29	1.11	1.45
1968/69	3.91	1.72	1.66	59	.25	15	.08	.67	1.01	.23	26e	87	.95
1969/70	3.22	2.13	85	53	76	40	.44	86	38	29	59	.69	93
1970/71	2.58e	1.17	41	18	14	.33	.19	08e	58	.28	25	26	54
1971/72	1.62	1.79	71	67	.27	17	.11	04	05	20	07	27	50
1972/73	1.46	3.29	84	42	.23	.33	.66	1.18	69	81	70	.40	92
1973/74	4.40	3.06	69	.50	34e	12	12	.20	14	09	74	98	95
1974/75	-	-	-	41	17	20	27	-	01	.04	01	12	-
1975/76	1.85	2.73	1.44	1.12	.28	36	.25	.13	.20	.16	09	28	74
1976/77	.81	.97e	71	44e	59	67	.14	05	12	48	1.32	69	58
1977/78	1.00	1.54e	2.12	69	.10	1.68	.44	.31	.31	.74	-		-
1978/79	2.18	1.63	.39	22	.15	.02	.00	2.36	2.68	.63	53	65	95
1979/80	1.76	2.94	3.06	58	21	.10	.13	.17	-	.09	49	.61	-
1980/81	.71	1.49	.42	08	.03	.08	-	-	10	-	.02	.12	-
1981/82	1.66	-	-	-	-	-	-	-	-	.07	-	-	-
1982/83	-	-	-	-	-	-	-	-	1.78	.44	.71	4.37	-
1983/84	-	-	1.05	.25	.13	.10	.07	.09	.29	2.78	.65	.10	-
1984/85	1.37	1.97	.31	.07	.06	.06	.08	.56	.29	.11	.98	.12	.49
1985/86	1.23	1.41	.08	.07	.09	.05	.09	.71	.64	1.36	.29	1.03	.59
1986/87	4.47	3.71	.44	.06	.07	.07	.10	.40	1.18	1.29	.09	-	-
1987/88	.42	.97	.07	05	.08	.07	.07	.14	.15	.92	1.31	1.71	.50
1988/89	3.63	63	.10	.06	.08	.08	.10	-	3.11	4.20	.22	.87	-
1989/90	7.53	-	-	-	-	-	-	-	-	-	-	-	-
Mean	2.22	1.92	.84	43	.27	.29	.25	.64	63	.59	.43	.69	.77
Median	1.76	1.54	.70	.38	.21	.16	.14	.31	.29	.28	.26	.47	
Maximum	7.53	3.71	3.06	1.45	1.35	2.13	97	3.78	3.11	4.20	1.32	4.37	
Minimum	.42	.63	.07	05	.03	.02	.00	.04	.01	00	.01	.10	
St. dev.	1.45	.95	.66	.35	.25	.44	.25	.86	.74	.83	.37	.79	
CV	.65	.49	79	.83	.93	1.50	1.00	1.34	1.19	1.40	85	1.14	

Mean monthly flow in cubic metres per second

Table A.2 Mean monthly flows for Mgeta at Mgeta

Institute of Hydrology
Summary of monthly data - Flow

Station number : 212 Name : Mgeta at Mgeta

Basin no. : 0 Latitude : 7: 2:40 S Longitude : 37:34 0 E Altitude : 975.0
Area 101.0

	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Annual Mean
1954/55	-	-	2.44	1.78	1.47	1.15	1.20	2.08	1.47	1.21	2.47	1.90	-
1955/56	3.66	5.29	3.09	2.18	1.73	1.38	1.28	3.20	2.84	4.30	3.43	3.57	2.99
1956/57	4.61	4.21	-	-	1.62	1.40	1.25	2.69	3.24	3.03	3.71	5.65	-
1957/58	5.09	5.29	3.36	2.30	1.99	1.97	1.52	2.12	2.49	1.93	1.91	2.64	2.72
1958/59	4.84	3.45	2.30	1.67	1.30	1.13	.92	1.38	3.38	2.10	1.76	1.81	2.17
1959/60	3.76	2.75	1.64	1.39	1.49	1.20	1.38	1.28	1.69	3.50	1.49	3.77	2.12
1960/61	7.03	2.85	2.00	1.44	1.14	.94	1.33	.97	.66	.77	3.47	2.78	2.10
1961/62	4.82	2.93	1.70	1.56	1.18	1.39	6.80	29.06	4.93	-	-	-	-
1962/63	3.40	3.21	2.06	1.68	1.98	1.54	1.67	1.94	-	-	-	-	-
1963/64	-	-	1.95	1.29	1.03	.73	.69	3.27	2.57	3.04	2.02	3.26	-
1964/65	6.96	3.00	1.81	1.26	1.00	.85	1.10	.73	1.06	1.60	1.31	1.49	1.84
1965/66	5.69	2.68	1.73	1.28	1.12	1.23	1.81	3.77	3.05	3.70	-	5.10	-
1966/67	8.50	-	2.36	1.53	1.17	1.06	1.51	1.42	1.50	.85	1.50	1.28	-
1967/68	3.59	4.58	3.18	2.13	1.80	3.59	2.47	4.34	3.49	2.51	2.09	4.36	3.16
1968/69	9.40	4.55	3.62	1.79	1.25	1.01	.85	2.63	2.51	1.48	1.84	4.45	2.94
1969/70	4.83	5.49	1.96	1.24	.98	.78	.74	1.79	1.54	1.95	3.99	3.39	2.36
1970/71	5.72	3.11	1.79	1.26	.98	1.71	1.15	1.09	4.74	1.23	.89	.54	2.02
1971/72	4.52	3.29	1.38	1.08	.73	.59	.61	.40	1.56	1.74	.33	.81	1.42
1972/73	3.52	4.27	1.44	.39	.21	.31	1.13	2.51	1.39	4.28	1.55	1.22	1.85
1973/74	5.81	6.52	2.11	1.04	1.01	.60	.64	1.93	2.46	1.51	1.10	1.42	2.19
1974/75	4.96	5.09	1.98	1.35	1.12	.59	1.09	1.17	1.16	2.03	1.20	1.77	2.00
1975/76	6.16	5.22	3.22	1.86	1.34	1.31	1.14	1.30	1.27	.57	.56	3.07	2.25
1976/77	5.34	4.23	2.16	1.78	1.46	1.47	1.59	1.23	2.06	2.68	2.14	1.95	2.34
1977/78	2.69	2.49	1.52	1.07	.86	1.81	1.41	5.30	6.52	4.43	2.99	3.69	2.90
1978/79	6.59	3.41	1.91	1.34	1.03	.82	.75	4.19	9.81	3.82	5.31	6.65	3.75
1979/80	12.60	7.09	4.97	2.96	2.27	2.02	1.98	2.23	2.52	3.35	4.44	3.24	4.12
1980/81	4.08	5.10	2.74	2.16e	1.83	1.69	1.60	2.33	5.31	1.32	1.30	1.37	2.58
1981/82	2.25	35.88	1.39	.91	.74	.66	.71	.74	2.55	2.83	1.83	2.11	4.44
1982/83	4.34	3.61	1.79	1.44	.56	.67	5.24	3.55	5.89	3.16	2.06	1.90	2.86
1983/84	2.37	3.83	2.30	1.75	1.47	1.25	1.12	1.14	1.33	1.77	1.55	1.39	1.77
1984/85	4.13	4.35	2.15	1.81	1.51	1.33	1.85	5.39	3.21	4.41	2.94	3.06	3.01
1985/86	5.36	4.75	1.89	1.38	.96	.91	.92	2.79	2.93	2.05	1.58	2.29	2.32
1986/87	5.64	3.87	1.95	1.46	1.07	.76	.73	1.02	2.85	2.84	2.39	2.30	2.24
1987/88	2.51	3.42	2.18	1.76	1.07	.77	.69	1.30	.77	.83	.86	1.83	1.50
1988/89	-	-	-	-	-	-	-	-	-	-	-	-	-
1989/90	-	-	-	-	-	-	-	-	1.11	-	-	-	-
Mean	5.15	5.16	2.25	1.56	1.25	1.21	1.50	3.01	2.82	2.40	2.13	2.69	2.59
Median	4.83	4.21	2.00	1.46	1.14	1.13	1.15	1.94	2.51	2.05	1.84	2.29	
Maximum	12.60	35.88	4.97	2.96	2.27	3.59	6.80	29.06	9.81	4.43	5.31	6.65	
Minimum	2.25	2.49	1.38	.39	.21	.31	.61	.40	.66	.57	.33	.54	
St. dev	2.14	5.81	.76	.47	.43	.59	1.24	4.78	1.91	1.16	1.17	1.44	
CV	.41	1.13	.34	.30	.35	.49	.83	1.59	.68	.48	.55	.53	

Mean monthly flow in cubic metres per second

Table A.3 Mean monthly flows for Wami at Dakawa

Institute of Hydrology
Summary of monthly data - Flow

Station number : 211 Name : Wami at Dakawa

Basin no : 0 Latitude : 6 26: 0 S Longitude : 37.32 0 E Altitude : 380 0
Area : 28500

	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Annual Mean
1953/54	-	-	-	-	-	-	-	-	3.59	17.56	9.27	10.24	-
1954/55	10.37	23.56e	11.00	6.15	4.26	2.79	2.39	1.73	2.19	1.33	29.69	20.43	9.53
1955/56	50.47	64.95	28.71	13.02	8.08	5.26	3.79	3.92	4.30	25.46	-	-	-
1956/57	77.11	73.38	31.79	18.25	12.54	8.70	6.15	5.81	4.93	11.19	21.42	13.28	23.65
1957/58	93.94	130.61	34.02	19.31	14.04	9.63	6.98	6.39	11.86e	-	-	-	-
1958/59	-	-	25.42	-	-	-	-	-	-	7.54	11.33	23.11	-
1959/60	26.66	19.40	10.01	6.18	5.23	4.06	2.81	1.96	3.92	13.54	7.74	17.09	9.88
1960/61	123.56	34.59	15.32	13.71	7.73e	5.53	4.02	3.35	1.87	1.50	9.55	12.08	19.29
1961/62	20.84	38.39e	11.32	8.82	6.26	4.66	6.06	40.23	50.19	177.98	55.65	83.60	45.53
1962/63	73.62	78.82	30.62	20.73	17.10	13.53	9.08	6.83	7.01	24.04	27.91	54.97	30.37
1963/64	140.24	70.68	29.33	21.33	14.64	11.49	8.07	20.17	40.52	56.72	63.54	62.58	44.73
1964/65	186.38	75.97	37.74	24.35	19.13	14.19	10.79	7.64	6.13	19.44	11.44	15.93	36.02
1965/66	59.13	24.36	16.29	9.29	7.42	5.42	5.98	6.20	10.85	22.18	28.26	47.73	20.18
1966/67	117.91	48.19	29.30	16.79	13.05	9.96	7.82	8.22	9.49	6.59	9.46	12.10	24.19
1967/68	70.78	112.32	53.83	24.79	18.38	17.32	14.01	16.63	137.74	134.12	47.97	116.48	64.05
1968/69	254.26	121.02	91.33	-	30.85	21.11	15.42	16.87	32.61	14.71	21.05	23.94	-
1969/70	38.78	97.78	25.26	16.67	12.70	9.62	7.29	6.90	6.07	32.88	51.89	56.02	30.09
1970/71	83.63	29.45	15.33	11.06	8.26	7.54	5.64	3.60	7.81	16.00	28.28	10.63	18.77
1971/72	51.06	34.19	15.14	11.94	7.97	6.07	4.47	3.25	4.64	14.63	9.98	25.27	15.71
1972/73	67.50	71.81	33.60	16.33	11.04	10.15	10.05	11.54	33.80	73.25	51.33	40.94	35.88
1973/74	52.45	86.21	34.36	20.93	15.63	9.27	5.86	4.49	6.36	4.10	6.01	2.92	20.79
1974/75	39.63	80.85	26.52	15.77	9.05	5.65	4.48	3.17	2.49	6.16	2.24	13.60	17.58
1975/76	22.92	23.64	10.50	4.89	3.39	3.04	2.42	2.01	3.94	7.75	10.21	16.06	9.22
1976/77	31.49	42.56	13.96	7.46	4.74	3.51	3.08	2.41	2.21	15.55	32.27	18.59	14.70
1977/78	26.06	29.71	10.75	5.28	4.15	3.54	2.84	4.06	15.35	33.82	17.76	23.83	14.78
1978/79	68.39	44.62e	20.46	12.35	8.17	4.83e	3.65e	9.91	74.53	71.75	94.24	90.72	41.69
1979/80	121.31	89.13	71.38e	43.14e	27.58	19.57	12.28	9.10	10.13	15.61	29.03	23.15	39.21
1980/81	34.26	50.96	16.95	9.91	6.65	-	-	-	14.25	10.45	12.36	9.16	-
1981/82	54.51	64.89	22.30	12.10	8.92	7.30	5.70	-	-	9.25	6.42	6.91	-
1982/83	20.26	28.78	-	-	9.00	7.93	15.58	20.57	50.25	77.97	25.67	38.74	-
1983/84	47.80	45.99	34.24	17.90	14.48	9.31	8.00	6.92	-	29.97	-	9.82e	-
1984/85	31.58	49.96e	13.93	10.81	9.31	7.89	7.01	17.42	34.35	44.64	27.12	26.39	23.40
1985/86	52.18	52.09	-	13.86	10.17	9.10	8.10	7.94	22.01	36.75	15.22	19.34	-
1986/87	63.79	43.07	31.09	15.39	11.52	8.79	6.93	7.95	38.38	79.41	44.92	31.51	31.83
1987/88	50.25	42.67	19.87	12.15	9.99	7.82	7.24	6.74	7.26	-	12.23	-	-
1988/89	34.62	9.88	9.22	7.49	6.38	6.36	-	-	-	-	-	-	-
Mean	67.59	56.88	26.69	14.69	11.11	8.51	7.00	8.84	21.91	33.75	25.98	30.66	26.12
Median	52.18	48.39	25.26	13.02	9.05	7.89	6.15	6.83	7.81	17.56	21.05	20.43	
Maximum	254.26	130.61	91.33	43.14	30.85	21.11	15.58	40.23	137.74	177.98	94.24	116.48	
Minimum	10.37	9.88	9.22	4.89	3.39	2.79	2.39	1.73	1.87	1.33	2.24	2.92	
St. dev	50.88	30.14	17.62	7.56	6.16	4.49	3.58	7.90	30.11	39.11	20.65	26.62	
CV	.75	.53	.66	.51	.55	.53	.51	.89	1.37	1.16	.79	.87	

Mean monthly flow in cubic metres per second